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Dependent Typing through Closed Cartesian Categories

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Dependent Typing through Closed Cartesian Categories

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Pedro Bonilla Nadal *Dependent Typing through Closed Cartesian Categories*

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Part I

Category Theory

Chapter 1

First Notions of Category Theory

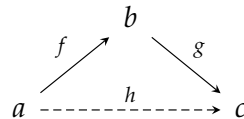
“The human mind has never
invented a labor-saving machine
equal to algebra.”

Stephan Banach (1925)

For us Category Theory is an area of interest on its own rights, rather than merely an elegant tool. Thus, we will introduce this theory with a point of view that emphasize the intuitive ideas behind each notion.

With this objective in mind, we will get into the habit of introducing the first examples even before introducing the formal definitions. Thus, when the formal definition is introduced it becomes meaningful.

The fundamental idea of Category Theory is that many properties can be unified if expressed in arrow diagrams. Intuitively, a diagram is a directed graph, such that each way of going from a node to another are equals. For example, the diagram:



Means that $f \circ g = h$. This approach to mathematics emphasises at the relationships between elements, rather than at the structure of the elements themselves. In general, dashed lines means that the existence of that particular arrow is uniquely determined by the solid arrow presents in the diagram.

In this first chapter we introduce the notion of category and some useful properties. The principal references for this chapter are [22] and [26]. Haskell references can be checked in [24].

1.1 Metacategories

We will start by defining a concept independent of the set theory axioms: the concept of *metacategory*. Then, categories will arise from studying these concepts within set theory. We follow [22] for these definitions.

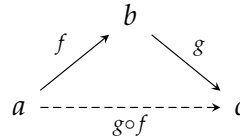
Traditionally, mathematics is based on the set theory. When we start set theory it is not necessary (it is not possible) to define what a set is. It is similar with the concepts of element and belonging, which are basic to set theory. Category theory

can also be used to found mathematics. This theory provide meaning based on other concepts such as object, arrow or composition rather than sets or belonging.

Definition 1.1.1. A *metagraph* consist of *objects*: a, b, c, \dots and *arrows* f, g, h, \dots . There are also two pairings: *dom* and *codom*. This pairings assigns each arrow with an object. An arrow f with $\text{dom}(f) = a$ and $\text{codom}(f) = b$ is usually denoted as $f : a \rightarrow b$.

Definition 1.1.2. A *metacategory* is a metagraph with two additional operations and two properties::

- Operations:
 - *Identity*: assigns to each object a an arrow $1_a : a \rightarrow a$.
 - *Composition*: assigns to each pair of arrows f, g with $\text{codom}(f) = \text{dom}(g)$ and arrow $g \circ f$ such that the diagram:



commutes. The arrow $g \circ f$ is called the *composite* of f and g .

- Properties:
 - *Associative*: given arrows f, g, h , we have that,

$$(g \circ f) \circ h = g \circ (f \circ h).$$

- *Unit*: given an object a , and arrows f, g such that $\text{dom}(f) = a$ and $(g) = a$, we have that,

$$1_a \circ g = g, \quad f \circ 1_a = f.$$

In the context of categories and metacategories, arrows are often called *morphisms*.

We have just define what a metacategory is without any need of set and elements. In most cases we will rely in a set theory interpretation of this definitions, as most examples (specially with our interest in computational example) will rely on this theory. Nonetheless, whenever possible, we will define the concepts working only in terms of objects and arrows.

1.2 Set theory categories

Despite being an alternative foundation of mathematics, in general we will work with categories interpreted with notions of set theory. Unless otherwise stated, we will use the Zermelo-Fraenkel axiomatics with Axiom of Choice. We recommend [20] for more information.

We have no interest in this work in the reformulation of axioms. Note that we have defined a meta-category without the need for notions of sets. In the same way, many definitions and propositions relating to this theory can be considered without

the need for notions of sets.

Further on we will work based on set theory. Despite that, it is useful to take into account that most of the concept here presented can be defined without making use of this Theory.

Definition 1.2.1. A category (resp. graph) is an interpretation of a metacategory (resp. metagraph) within set theory.

That is, a graph/category is a pair (O, A) where O is a collection of all objects as well as a collection A consisting of all arrows. Their elements hold the same properties that objects and arrows hold on metacategories / metagraph.

We will focus on the category. First, we define the function hom_C of a category $C = (O, A)$, wrote as hom_C , as the function:

$$\begin{aligned} \text{hom}_C : O \times O &\mapsto \mathcal{P}(A) \\ (a, b) &\mapsto \{f \in A \mid f : a \rightarrow b\} \end{aligned}$$

When there is no possibility of confusion we will state $c \in C$ without specifying . We will refer to the collection of objects of a category C as $Ob(C)$ and the collection of arrows as $Ar(C)$.

Definition 1.2.2. We say that a category is *small* if the collection of objects is given by a set (instead of a proper class). We say that a category is *locally small* if every homsets is a set.

We proceed to introduce a comprehensive list of examples, so that it is already introduced in subsequent chapters.

Example 1.2.1.

- The elementary categories:
 - The category $0 = (\emptyset, \emptyset)$ where every property is trivially satisfied.
 - The category $1 = (\{e\}, \{1_e\})$.
 - The category $2 = (\{a, b\}, \{1_a, 1_b, f : a \rightarrow b\})$
- Discrete categories: are categories where every arrow is an identity arrow. This are sets regarded as categories, in the following sense: every discrete category $C = (A, \{1_a : a \in A\})$ is fully identified by its set of object.
- Monoids and Groups: A monoid is a category with one object (regarding the monoid of the arrows). In the same way, if we requires the arrows to satisfy the inverse property, we can see a group as a single-object category.
- Preorder: From a preorder (A, \leq) we can define a category $C = (A, B)$ where B has an arrow $e : a \rightarrow b$ for every $a, b \in A$ such that $a \leq b$. The identity arrow is the arrow that arise from the reflexive property of the preorders.
- Large categories: these categories has a large set of objects. For example:
 - The category *Top* that has as objects all small topological spaces and as arrow continuous mappings.

- The category *Set* that has as objects all small sets and as arrows all functions between them. We can also consider the category *Set*_{*} of pointed small sets (sets with a distinguished point), and function between them that maps one distinguished point into another.
- The category *Vect* that has as object all small vector spaces and as arrows all linear functions.
- The category *Grp* that has as object all small vector group and as arrows all homomorphism.
- The category *Top*_{*} that has as object all small topological spaces with a distinguished point, and as arrow all continuous functions that maps each distinguished points into distinguished points. Similarly we can consider *Set*_{*} or *Grp*_{*}.
- The category *Grph* that has as objects all small graphs, and as arrows all graphs morphisms.
- The category *Hask* of all Haskell types and all possible functions between two types.

Note that, for example, as natural numbers can be seen as either a set or a preorder, they also can be seen as a discrete category or a preorder category.

Simple enough categories can be easily described with diagrams: there are as many objects as nodes in the diagram and an arrow in the category for each:

- Arrow in the diagram.
- Composition of existing arrows.
- Every node (identity arrow usually omitted in diagrams).

For example, we can fully represent the 2 category with the diagram:

$$a \xrightarrow{g} c$$

1.2.1 Properties

We can see that is common in mathematics to have an object of study (propositional logic clauses, groups, Banach spaces or types in Haskell). Once the purpose of studying these particular sets of objects is fixed, it is also common to proceed to consider the transformations between these objects (partial truth assignments, homomorphisms, linear bounded functionals or functions in Haskell).

In categories, we have a kind of different approach to the subject. Instead of focusing on the objects themselves, we focus on how they relate to each other. That is, we focus on the study of the arrows and how they composes. Therefore we can consider equal two objects that has the same relations with other objects. This inspire the next definition:

Definition 1.2.3. [26, Definition 1.1.9] Given a category $C = (O, A)$, a morphism $f : a \rightarrow b \in A$ has a *left inverse* (resp. *right inverse*) if there exists a $g : b \rightarrow a \in A$ such that $g \circ f = 1_b$ (resp. $f \circ g = 1_a$). A morphism is an *isomorphism* if it has both left and right inverse, called the *inverse*. Two object are isomorphic if there exists an isomorphism between them.

Is easy to follow that if a morphism has a left and a right inverse, they must be the same, thus implying the uniqueness of the inverse. Also one can see that this functions define bijections between $\text{hom}(a, c)$ and $\text{hom}(b, c)$ for all $c \in O$.

We will now proceed to talk about certain arrows and objects that have properties that distinguish them from others. The most useful example to gain an intuition of these properties is that of the *FinSet* category, of all finite sets and functions between them. Considering special arrows:

Definition 1.2.4. An arrow f is *monic* (resp. *epic*) if it is *left-cancelable* (resp. *right-cancelable*), i.e. $f \circ g = f \circ h \implies g = h$ (resp. $g \circ f = h \circ f \implies g = h$).

In *FinSet* this arrows are the injective functions (resp. surjective). Considering special objects:

Definition 1.2.5. an object a is *terminal* (resp. *initial*) if for every object b there exists an unique arrow $f : b \rightarrow a$ (resp. $f : a \rightarrow b$). An object that is both terminal and initial is called *zero*.

In *FinSet* this objects is the initial object is the empty set and the terminal object the one point set. In the *Pointed*

Proposition 1.2.1. Every two terminal object are isomorphic.

Proof. Every terminal object has only one arrow from itself to itself, and necessarily this arrow has to be the identity. Let a, b be terminal object and $f : a \rightarrow b$ and $g : b \rightarrow a$ be the only arrows with that domain and codomain. Then $f \circ g : a \rightarrow a \implies f \circ g = 1_a$. Analogously $g \circ f = 1_b$. □

Another important property is the *duality property*. This property tell us that for every theorem that we prove for categories, there exist another theorem that is automatically also true. To formalize this idea, we define the concept of *opposite category*.

Definition 1.2.6. [26, Definition 1.2.1] Let C be any category. The opposite category C^{op} has:

- the same objects as C ,
- an arrow $f^{op} \in C^{op}$ for each arrow $f \in C$, so that the domain of f^{op} is defined as the codomain of f and viceversa.

The remaining structure of the category C^{op} is given as follows:

- For each object a , the arrow 1_a^{op} serves as its identity in C^{op} .
- We observe that f^{op} and g^{op} are composable when f and g are, and define $f^{op} \circ g^{op} = (g \circ f)^{op}$

The intuition is that we have the same category, only that all arrows are turned around. We can see that for each theorem T that we prove, we have reinterpretation that theorem to the opposite category. Intuitively this theorem is an equal theorem in which all the arrows have been turned around. For example: the proposition 1.2.1 can be reworked as:

Proposition 1.2.2. Every two initial object are isomorphic.

That is because being initial is the dual property of being terminal, that is, if $f \in C$ is a terminal object then $f^{op} \in C^{op}$ is an initial object. The property “being isomorphic” is its own dual.

1.2.2 Transformation in categories

This is one of the main ways of defining a category: consider a collection of objects and the standard way of transforms one into each other. Then, we may also follow our study defining the structure preserving transformation of categories.

Definition 1.2.7. Given two categories C, B , a *functor* $F : B \rightarrow C$ is a pair of functions $F = (F' : Ob(B) \rightarrow Ob(C), F'' : Ar(B) \rightarrow Ar(C))$ (the *object function* and the *arrow functor* respectively) in such a way that:

$$F''(1_C) = 1_{F'C}, \forall C \in Ob(C); \quad F''(f \circ g) = F''f \circ F''g, \forall f, g \in Ar(C).$$

That is, a functor is a morphism of categories. When there is no ambiguity we will represent both F' and F'' with a single symbol F acting on both objects and arrows. Also, it can be seen in the definition that whenever possible the parentheses of the functor will be dropped. This loss of parentheses will be replicated thorough the text, whenever possible.

An important consideration on functors is that a functor F can be defined only pointing out how it maps arrows (assuming that such mapping respects the composition), as how F maps object can be defined with how it map identity arrows.

Lets provide some examples of functors:

Example 1.2.2.

- Forgetfull functor: We have a variety of categories consisting of structures with sets as objects and functions that hold structure such as arrows (eg Top , Grp or $Vect$).

Let C one of such categories, then we have a functor $F : C \rightarrow Set$ that maps each object to its underlying set and each arrow to the equivalent arrow between sets. That is, this functor forgets about the structure that is present in C .

Additionally, we will often have functors defined $F : C \rightarrow Set$. For some cases of C it also happen that FC has some more structure on it. In that case we will say that F is an enriched functor for that cases.

Another similar case of Forgetful functor is $\mathcal{U} : Cart \rightarrow Grph$ that maps each (small) category to their *underlying* graph.

- Fundamental Group: In the context of algebraic topology we have the functor of the fundamental group $\Pi_1 : Top_* \rightarrow Grp$. The most famous property of this function is that

Given continuous application $f, g : X \rightarrow Y$ between two topological spaces induces an application of the group of loops of X on the group of loops of Y such that $\Pi_1(f \circ g) = \Pi_1(f) \circ \Pi_1(g)$.

that is, the functoriality of the function (taking also into account the fact that the identity of topological spaces is mapped to the identity of group).

- Stone-Čech Compactification: In the realm of functional analysis we have the following theorem:

Theorem 1.2.1. *Let Ω be a completely regular Hausdorff topological space. Then there exists a compact Hausdorff topological space $\beta\Omega$ and a homeomorphism Φ , from Ω to a dense subset of $\beta\Omega$. Moreover, for every continuous and bounded function $f : \Omega \rightarrow \mathbb{K}$ there exists a unique $\bar{f} \in C(\beta\Omega)$ such that $\bar{f} \circ \Phi = f$ and the application $f \rightarrow \bar{f}$ is an isometric isomorphism. Finally, $\beta\Omega$ is uniquely determined up to isomorphisms by the above properties.*

Remark 1.2.1. Where $\Delta(t) = \delta_t$ denotes Dirac's operator.

Proof. It is enough to take as $\beta\Omega$ the closure of $\Delta(\Omega)$ in the induced weak-topology ω^* (since in the weak topology we have that a bounded closed is compact).

Given a continuous and bounded function $f : \Omega \rightarrow K$ we can define the function \bar{f} by injection of Ω and then limit to maintain continuity (which will exist by compactness and boundedness of f). Thus the maximum of \bar{f} can be reached by a sequence of points injected from Ω obtaining that

$$\max \{ |\bar{f}(s)| : s \in \beta\Omega \} = \sup \{ |f(s)| : s \in \Omega \}.$$

The application $f \rightarrow \bar{f}$ is therefore an isometric isomorphism. Thanks to this isometric isomorphism the function spaces and by the Banach-Stone theorem[2, Theorem 3] we have uniqueness up to isomorphisms. \square

Based on this theorem we can define a functor $\beta : Hauss \rightarrow Comp$ where *hauss* is the category of Completely regular Hausdorff Spaces and continuous functions, and *Comp* the category of Compact Hausdorff Spaces along with continuous function. This functor:

- Take an object $\Omega \in Hauss$ to $\beta(\Omega) = \beta\Omega$:
- Take an arrow $f : \Omega \rightarrow \Omega' \in Hauss$ to $\Delta(f)$ and the complete by continuity.
- Group actions: Every group action can be seen as a functor from a Group to a Set.

Let G be a group seen as a category with only one element and S be a set seen as a discrete category. Then, an action is a representation of the group of the endomorphism of the set, that is, an action α associate each element of the group with an function $\alpha(g) : X \rightarrow X$ such that the product of element of the group is maintain via composition. That is for $g \in Ar(G)$ we have that $\alpha(g) \in Ar(X)$ and for

$$\alpha(g \circ^1 f) = \alpha(g) \circ \alpha(f) \quad \forall g, f \in Ar(G),$$

where in 1. it is to note that is a group seen as a category the product is the composition) thus having the functoriality.

- Maybe Method in Haskell [24, Section 7.1]): In Haskell the definition of Maybe is a mapping from type a to type `Maybe a`.

```
data Maybe a = Nothing | Just a
```

LISTING 1.1: Declaration of Maybe

Note that `Maybe a` is not a type but a function of types. In order for it to be an endofunctor of the *Hask* category we will need for it to also map function. Let $f : a \rightarrow b \in \text{Hask}$, then we define the function

$$\text{Maybe } f : \text{Maybe } a \rightarrow \text{Maybe } b$$

such that

$$(\text{Maybe } f)(\text{Nothing}) = \text{Nothing}, \quad (\text{Maybe } f)(\text{Just } a) = \text{Just } f(a).$$

Note that $(\text{Maybe } id_a)(\text{Maybe } a) = \text{Nothing} \mid \text{Just } id_a(a) = \text{Maybe } a$.

We can now construct the category of all small categories *Cat*. This category has as object all small categories and as arrows all functor between them. Note that *Cat* does not contain itself.

We can consider some properties in functors. Note that we can consider a functor $T : C \rightarrow D$ as a function over homeset, that is, a function:

$$T : \text{hom}_C(a, b) \rightarrow \{Tf : Ta \rightarrow Tb \mid f \in C\} \subset \text{hom}_D(Ta, Tb)$$

Definition 1.2.8. A functor $T : C \rightarrow D$ is *full* if it is surjective as a function over homesets, i.e. if the function $T : \text{hom}_C(a, b) \rightarrow \text{hom}_D(Ta, Tb)$ is surjective for every $a, b \in C$. A functor is *faithfull* if it is injective over homesets.

As we have defined the concept of opposite category, we can consider functors $T : C^{op} \rightarrow D$. This functor, is called a *contravariant* functor from C to D .

We shall continue defining natural transformation. In the words of Saunders Mac Lane:

Category has been defined in order to define functor and functor has been defined in order to define natural transformation.

One can see a functor $T : C \rightarrow D$ as representation of a category in another, in the sense that a functor provide a picture of the category C in D . Further into this idea, we can consider how to transform these drawings into each other.

Definition 1.2.9. Given two functor $T, S : C \rightarrow D$, a *natural transformation* $\tau : T \Rightarrow S$ is a function from $Ob(C)$ to $Ar(D)$ such that for every arrow $f : c \rightarrow c' \in C$ the following diagram:

$$\begin{array}{ccc} Tc & \xrightarrow{\tau c} & Sc \\ \downarrow Tf & & \downarrow Sf \\ Tc' & \xrightarrow{\tau c'} & Sc' \end{array}$$

commutes. A natural transformation where every τc is invertible is called a *natural equivalence* and the functors are *naturally isomorphic*.

That is a natural transformation is a map from pictures of C in to pictures of D . Note that a natural transformation acts only on the domain of objects. Lets provide some examples.

When we have to define natural transformations it will often be useful to define each arrow individually. In this case, with the same notation as in the definition, we will note $\tau(c) = \tau_c : Tc \rightarrow Sc$.

Example 1.2.3.

- The opposite group: We can define the opposite functor $(\cdot)^{op} : Grp \rightarrow Grp$ that maps $(G, *)$ to $(G; *^{op})$ where $a *^{op} b = b * a$ and map a morphism $f : G \rightarrow G'$ we define $f^{op}(a) = f(a)$ and have that

$$f^{op}(a *^{op} b) = f(b * a) = f(b) * f(a) = f^{op}(a) *^{op} f^{op}(b).$$

Denoting the identity function $Id : Grp \rightarrow Grp$, we have a natural transformation $\tau : Id \Rightarrow (\cdot)^{op}$ defined by $\tau_G(a) = a^{-1}$ for all $a \in G$.

- In Haskell, the `safeHead` [24, Section 10.1] function between the `List` functor and the `Maybe` functor. Lets start by defining the functors:
 - We can define the list functor that maps the type a to the type $[a]$ and apply each function $f : a \rightarrow b$ to $f' : [a] \rightarrow [b]$ that applies f elements wise (on empty list it does nothing).

```
data List a = Nil | Cons a ( List a)
```

- We can define the natural transformation `SafeHead : List → Maybe` defined as follow:

```
safeHead :: [a] -> Maybe a
safeHead [] = Nothing
safeHead (x : xs) = Just x
```

1.2.3 Constructions

In this last subsection we will introduce some standard construction on categories, along with some examples of these constructions.

Product Category

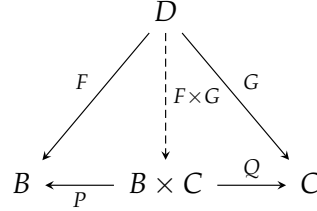
We present now one of the most usual construction in mathematics: the product. We will consider the “universal” properties of product on the next chapter. By now, we present the product of categories.

Definition 1.2.10. Let B, C be categories. Then the *product category* $B \times C$ is the category that has as objects the pairs $\{\langle b, c \rangle : b \in Ob(B), c \in Ob(C)\}$ and as arrows the pairs of arrows $\{\langle f, g \rangle : f \in Ar(B), g \in Ar(C)\}$. The composition of arrows is defined by the elementwise composition.

It is clear that we can define to functor $P : B \times C \rightarrow B$ and $Q : B \times C \rightarrow C$ that restricts the category to each of its component parts (functorial axioms follow immediately). Moreover, we can see that any functor $F : D \rightarrow B \times C$ will be uniquely

identified by its composition by P and Q .

Complementary, for any two functors $F : D \rightarrow B, G : D \rightarrow C$ we can define an functor $F \times G : D \rightarrow B \times C$ that apply $(F \times G)\langle f, g \rangle = \langle Ff, Gg \rangle$. Expressed as a diagram:



A functor $F : B^{op} \times C \rightarrow D$ is called a *bifunctor*. Arguably the most important bifunctor is the hom_C function seen as a functor. Given a category C we can see $\text{hom}_C : C^{op} \times C \rightarrow \text{Set}$ as a bifunctor such that:

$$\text{hom}_C(\cdot, \cdot)(a, b) = \text{hom}_C(a, b) \quad \forall a, b \in \text{Ob}(C)$$

for the object. For the arrows:

$$\begin{aligned} \text{hom}_C(f^{op}, g) : \text{hom}_C(a', b) &\rightarrow \text{hom}_C(a, b') & \forall f : a \rightarrow a', g : b \rightarrow b' \in C \\ \text{hom}_C(f^{op}, g)(h) &= g \circ h \circ f & \forall h \in \text{hom}_C(a', b) \end{aligned}$$

From this bifunctor we can define two functors for every $c \in \text{Ob}(C)$:

- The functor $\text{hom}_C(c, \cdot) : C \rightarrow \text{Set}$ such that

$$\text{hom}_C(c, \cdot) = \text{hom}_C(c, d) \quad \forall d \in \text{Ob}(C)$$

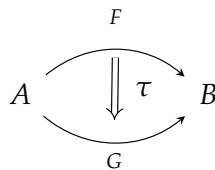
$$\begin{aligned} \text{hom}_C(c, g) : \text{hom}_C(a, d) &\rightarrow \text{hom}_C(a, d') & \forall g : d \rightarrow d' \in C \\ \text{hom}_C(c, g)(h) &= g \circ h & \forall h \in \text{hom}_C(c, d) \end{aligned}$$

- The covariant functor $\text{hom}_C(\cdot, c) : C^{op} \rightarrow \text{Set}$, defined analogously.

Functor Categories

We continue defining functor categories, that is, categories where we consider the functors as objects and natural transformation as arrows in some sense. This concept will be instrumental in further consideration in the realm of functional programming (in particular, in the definition of monad).

Before explaining composition between natural transformation, it is useful to present the following diagram. Let B, C be categories, $F, G : B \rightarrow C$ be functors and $\tau : F \rightarrow G$ natural transformation τ , it is common to represent this structure with:



Lets define the composition of two natural transformation. We will start defining the composition of two natural transformations σ, τ as in:

$$\begin{array}{ccc}
 & F & \\
 & \Downarrow \tau & \\
 A & \xrightarrow{G} & B \\
 & \Downarrow \sigma & \\
 & H &
 \end{array}$$

Due to this representation, this composition of natural transformations is called *vertical composition*, in opposition to the *horizontal composition* (def. 1.2.13).

Definition 1.2.11. Let C and B be two categories, $R, S, T : C \rightarrow B$ be functors, and let $\tau : R \rightarrow S, \sigma : S \rightarrow T$, we define the composition $(\tau \circ \sigma)c = \tau c \circ \sigma c$.

To see that $(\tau \circ \sigma)$ is a natural transformation it suffices the following diagram[30]:

$$\begin{array}{ccc}
 Rc & \xrightarrow{Rf} & Rc' \\
 \sigma c \downarrow & & \downarrow \sigma c' \\
 Sc & \xrightarrow{Sf} & S(c') \\
 \tau c \downarrow & & \downarrow \tau c' \\
 Tc & \xrightarrow{Tf} & Tc'
 \end{array}$$

Definition 1.2.12. Let B, C be categories. We define the category B^C as the functor category from C to B , that is, the category with all functors $F : C \rightarrow B$ as object, natural transformation as arrows, and composition as defined in 1.2.11.

we now present some examples to provide some intuition about when this type of construction are considered.

Example 1.2.4.

- The category of group action over a set: As we have seen in 1.2.2 each group action over a set is a functor. Let G be a group and S be a set, both seen as categories. Then we can consider the category S^G , that has as object every group action of G over S and as arrow the morphism of actions.
- C^2 : In 1.2.1 we define the 2 category and can consider therefore the category of functor from 2 to C . This category is called the arrow category, as the can see that there are a functor from 2 to C as functor for each arrow in C and conversely.

This example display a interesting idea: we can consider small collection of object as functions/functors. This idea can as well be seen when we define a pair of real numbers as any function $f : \{0, 1\} \rightarrow \mathbb{R}$. Should we want, for example, to consider all the squares in a category C , we might as well define the category square Sqr and consider every functor $F : Sqr \rightarrow C$.

Note that the elements $F : Sqr \rightarrow C$ are the arrows of the arrow category of C .

$$\begin{array}{ccc}
 a & \xrightarrow{f} & a' \\
 \downarrow g & & \downarrow h \\
 b & \xrightarrow{k} & b'
 \end{array}$$

The square category.

- We can use this construction to study the category C^C of endofunctors of a particular category C . This case is particularly interesting while studying the endofunctors present in $Hask^{Hask}$ and later consider the Monad as a programming structure.

Note that this is not the only way in which to define the composition of natural transformation. In fact, we can define another functor category. In this case we compose two natural transformation as in:

$$\begin{array}{ccccc}
 & F & & F' & \\
 B & \xrightarrow{\quad} & C & \xrightarrow{\quad} & D \\
 & G & & G' & \\
 & \tau & & \sigma &
 \end{array}$$

Lets formalize this composition:

Definition 1.2.13. Let B, C, D be categories, $F, G : B \rightarrow C, F', G' : C \rightarrow D$ be functors, and let $\tau : F \rightarrow G, \sigma : F' \rightarrow G'$, we define the composition $(\tau \circ \sigma) : F \circ F' \rightarrow G \circ G'$ such that

$$(\sigma \circ \tau)c = Fc \circ G'\tau c$$

for all $c \in B$.

With this horizontal composition we can properly defined. In this case we can see that the composition of two natural transformation is indeed a natural transformation due to the commutativity of:

$$\begin{array}{ccc}
 F'Fc & \xrightarrow{\sigma Fc} & G'Fc \\
 \downarrow F'\tau c & \searrow (\sigma \circ \tau)c & \downarrow G'\tau c \\
 F'Gc & \xrightarrow{\sigma Gc'} & G'Gc'
 \end{array}$$

With this definition of composition we can consider another different category: the category of all functors of all (small) categories, that is, the category that has all functors as object, and has the natural transformation with horizontal composition as arrows.

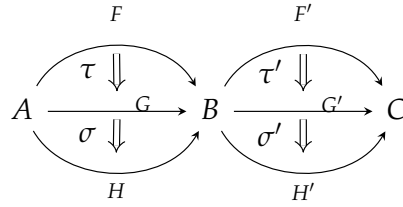
When we have to consider both compositions at the same time we denote the vertical composition with $\tau \cdot \sigma$ and horizontal composition with $\tau \circ \sigma$, as in [22]. Lastly we have to consider how this composition relate to each other. This is seen in the *interchange law*:

Proposition 1.2.3. Let A, B, C be categories, $F, G, H : A \rightarrow B, F', G', H' : B \rightarrow C$ be functors and $\tau : F \rightarrow G, \sigma : G \rightarrow H, \tau' : F' \rightarrow G', \sigma' : G' \rightarrow H'$ be natural

transformations, then:

$$(\sigma' \circ \sigma) \cdot (\tau' \circ \tau) = (\sigma' \cdot \tau') \circ (\sigma \cdot \tau)$$

Proof. We have a structure like



From the naturality of τ' we have that for all $c \in A$:

$$\begin{aligned} ((\sigma' \cdot \tau') \circ (\sigma \cdot \tau))(c) &= H'((\sigma \cdot \tau)c) \circ (\sigma' \cdot \tau')(Fc) \\ &= H'(\sigma c \circ \tau c) \circ (\sigma'(Fc) \circ \tau'(Fc)) \\ &= H'(\sigma c) \circ H'(\tau c) \circ \sigma'(Fc) \circ \tau'(Fc) \\ &= H'(\sigma c) \circ \sigma' Gc \circ G' \tau c \circ \tau'(Fc) \\ &= (\sigma' \circ \sigma)(c) \circ (\tau \circ \tau)(c) \\ &= ((\sigma' \circ \sigma) \cdot (\tau' \circ \tau))(c). \end{aligned}$$

□

To finally consider the relation between products, and the functor category we can see that given 3 small categories A, B, C we have a bijection:

$$\text{hom}_{Cat}(A \times B, C) \cong \text{hom}_{Cat}(A, C^B).$$

This fact will be taken into account further in the text, as this will mean that the functor $\cdot \times B : Cat \rightarrow Cat$ has a right adjoint.

Comma Category

To define the comma category, we define the Category $(b \downarrow S)$ of object S -under b , sketch the dual notion, and generalize this two concepts with the comma category.

Given a functor $F : B \rightarrow C$ an object $b \in B$ is F -under another object $c \in C$ if there exists an arrow $f : c \rightarrow Fb \in C$. This can be represented as

$$\begin{array}{c} c \\ \downarrow f \\ Fb \end{array}$$

and thus the name of F -under.

Definition 1.2.14. Let B, C be (small)¹ categories and $S : B \rightarrow C$ be a functor. For every $c \in Ob(C)$ we can define the category $(c \downarrow S)$ that has as objects all pairs $(b, f) \in Ob(B) \times Ar(C)$ such that $f : c \rightarrow Sb$ and as arrows $h : (d, f) \rightarrow (d', f')$ every arrow $h : d \rightarrow d' \in Ar(B)$ such that $f' = Sh \circ f$.

¹check this

The property that each arrow should satisfy can be represented as:

$$\begin{array}{ccc} & c & \\ f \swarrow & & \searrow f' \\ Sd & \xrightarrow{Sh} & Sd' \end{array}$$

Example 1.2.5. Let $U : Grp \rightarrow Set$ be the forgetful functor, and let $X \in Ob(Set)$. We can consider $(X \downarrow U)$ where every object is a function $f : X \rightarrow Ug$ for a group g .

One can easily now deduce the dual concept of the category $(b \uparrow S)$ represented by:

$$\text{objects: } \begin{array}{c} c \\ f \uparrow \\ Fb \end{array} ; \quad \text{arrows: } \begin{array}{ccc} & c & \\ f \swarrow & & \searrow f' \\ Sd & \xrightarrow{Sh} & Sd' \end{array} .$$

Now suppose that we have three categories B, C, D and two functors S, T such that

$$B \xrightarrow{S} C \xleftarrow{T} D$$

we might want to consider the relations objects of B and D , for that we have the comma category:

Definition 1.2.15. Let B, C, D be categories and two functors $S : B \rightarrow C, T : C \rightarrow D$. We define the comma category $(S \downarrow T)$ as the category that has as object the triples (b, d, f) with $b \in Ob(B), d \in Ob(D), f : Sb \rightarrow Td \in Ar(C)$ and arrows the pairs $(g, h) : (b, d, f) \rightarrow (b', d', f')$ with $g : b \rightarrow b' \in Ar(B), h : d \rightarrow d' \in Ar(D)$ such that $Th \circ f = f' \circ Sg$.

We can represent the previous definition by:

$$\text{objects: } \begin{array}{c} Sb \\ \downarrow f \\ Td \end{array} ; \quad \text{arrows: } \begin{array}{ccc} Sb & \xrightarrow{Sg} & Sb' \\ \downarrow f & & \downarrow f' \\ Td & \xrightarrow{Sh} & Td' \end{array} .$$

The name comma category comes from its alternative notation $(S \downarrow T) = (S, T)$. We prefer the $(S \downarrow T)$ as it is more clear, nonetheless it is clear that before modern text editor became popular, the original comma notation had a big plus.

Chapter 2

Universality, Adjoints and Closed Cartesian Categories

In this chapter we are going to study universality and adjunctions. Despite a possible apparent difference in definitions, both have the same use: they are tools that, given an arrow selected in a category, allow us to uniquely select an arrow in another category, generally fulfilling some special property (if not, a functor would be enough).

We will start this section with the definition of universality, as well as the statement of Yoneda's lemma. Then, we present the concept of Adjunction. We will use these concepts to introduce new structures, in particular that of closed Cartesian category.

2.1 Universality

In this section we present the concept of universality. This concept is behind lots of mathematical properties. Intuitively, universality is an efficient way of expressing an one-to-one correspondence between arrows of different categories. This one-to-one relationship is usually expressed via "given an arrow y it exists one and only one arrow x such that <insert your favorite universal property>".

Lets do an introductory example. Probably the first contact that any mathematician has with universality is defining a function $f : \mathbb{R} \rightarrow \mathbb{R}^2$. It is easy to see that defining such a function is equivalent to define two $g, h : \mathbb{R} \rightarrow \mathbb{R}$. Furthermore, those g, h are unique for each f . This uniqueness is the flavor that attempts to capture the concept of universality. Other examples of unique existence are those that occur in quotient groups or in bases of vector spaces.

Definition 2.1.1. Let $S : D \rightarrow C$ be a functor and $c \in Ob(C)$, an *universal arrow* from c to S is a pair (d, u) with $d \in Ob(D)$, $u : c \rightarrow Sd \in Ar(C)$, such that for every (e, f) with $e \in Ob(D)$ and $f : c \rightarrow Se$ there exists a unique $f' : d \rightarrow e \in Ar(D)$ such that $Sf' \circ u = f$.

In a diagram:

$$\begin{array}{ccc} c & \xrightarrow{u} & Sd \\ & \searrow f & \downarrow Sf' \\ & & Se \end{array} \quad \begin{array}{c} d \\ \downarrow f' \\ e \end{array}$$

Note that an universal arrow (d, u) induces the unique existence of an arrow in D , but with interesting properties via it relationship with S . Usually, to provide an universal arrow we will only define the functor $S : D \rightarrow C$ and the arrow $u : c \rightarrow Sd$, letting all other information be deduced from the context.

The idea of universality is often regard via the notion of *universal element*, in the special (and commonplace) case where $S : D \rightarrow \text{Set}$.

Definition 2.1.2. Let $S : D \rightarrow \text{Set}$, an *universal element* for S is a pair (r, e) with $r \in \text{Ob}(D), e \in Sr$, such that for every (d, x) with $d \in \text{Ob}(D), x \in Sd$, there is an unique arrow $f : r \rightarrow d \in D$ such that $(Sf)e = x$.

Note that having an universal element is a particular case of having an universal arrow. Considering $*$ the set with one point (as a category) an universal element is an universal arrow $* \rightarrow H$. This is clearly seen if we consider the diagram:

$$\begin{array}{ccc} * & \xrightarrow{u} & Sr \\ & \searrow f & \downarrow Sf \\ & & Sd \end{array} \quad \begin{array}{c} r \\ \downarrow f \\ d \end{array}$$

where $*$ is helping us select the elements of Sd and Se to enforce the property.

Conversely if D has small homesets, we can consider an universal arrow to be a particular case of an universal element. With the same context as in 2.1.1 $(d, u : c \rightarrow Sd)$ is an universal arrow if, and only if, $(d, u \in \text{hom}_D(c, Sd))$ is an universal element.

The point of having these such similar definition is to have different interfaces for the concept. While most result can be easily adapted, once we got to the examples is clear when to use each concept.

Example 2.1.1.

- **Quotient Group:** This property states that, for any two groups $N \triangleleft G$ with $\pi : G \rightarrow N$ the canonical projection, and any group homomorphism $f : G \rightarrow K$ such that $N \subset \ker f$ there exists an unique $\bar{f} : H \rightarrow K$ such that $\bar{f} \circ \pi = f$.

The question now is, how is this a universal property. This is an example of a universal element. Considering the functor $H : \text{Grp} \rightarrow \text{Set}$:

$$HG' = \{f : G \rightarrow G' \in \text{Ar}(\text{Grp}) : F(N) = \{0\}\},$$

Then, $(G/N, \pi)$ is an universal element for H . From this property alone the three isomorphism theorems can be deduced. Therefore, we only have to prove this result to have the full power of these theorems in any context (e.g. Rings, K-Algebra, or Topological spaces).

- **Tensor Product:** Given an right R -module A and a left R -module B one can consider the tensor product as an abelian group $A \otimes_R B$ and an R -biadditive function

$$h : A \times B \rightarrow A \otimes_R B,$$

such that for every R -biadditive $f : A \times B \rightarrow G$ it exists an unique \bar{f} such that $\bar{f} \circ h = f$. Is easy to follow that tensor product can be reformulated as an

universal arrow $\varphi : AB \rightarrow A \otimes_R B$ from $A \times B$ to the identity functor in the category of R -additive groups along with R -additive functions.

Dually, we can consider an *universal arrow from S to c* or simply universal arrow from S :

Definition 2.1.3. Let $S : D \rightarrow C$ be a functor and $c \in Ob(C)$, an *universal arrow from c to S* is a pair (d, u) with $d \in Ob(D)$, $u : c \rightarrow Sd \in Ar(C)$, such that for every (e, f) with $e \in Ob(D)$ and $f : c \rightarrow Se$ there exists a unique $f' : d \rightarrow e$ such that $u \circ Sf' = f$.

In a diagram:

$$\begin{array}{ccc} c & \xleftarrow{f} & Sd \\ & \searrow u & \downarrow Sf' \\ & & Se \end{array} \quad \begin{array}{c} d \\ \downarrow f' \\ e \end{array}$$

Example 2.1.2.

- In *Set* we have a particular construction: the product of sets for any two sets a, b along with the projections $\pi_1 a \times b \rightarrow a$ and $\pi_2 a \times b \rightarrow b$. Then, we can define the functor $\Delta : Set \rightarrow Set \times Set$ such that $\Delta c = c \times c$ for every $c \in Ob(Set)$ and $\Delta(f : c \rightarrow b) : c \times c \rightarrow b \times b$ is the elements-wise application of f .

Then, given any two sets $a, b \in Ob(Set)$, $u = (\pi_1, \pi_2)$ is an universal arrow from Δ to (a, b) as

$$\begin{array}{ccc} (a, b) & \xleftarrow{f} & \Delta d = (d, d) \\ & \searrow u & \downarrow \Delta f' \\ & & \Delta e = (e, e) \end{array} \quad \begin{array}{c} d \\ \downarrow f' \\ e \end{array}$$

This construction is reproducible in, among many others, *Grp*, *Top* or Banach Spaces with bounded linear transformation.

Lastly, we will provide a characterization of universality:

Proposition 2.1.1. Let $S : D \rightarrow C$ be a functor and $u : c \rightarrow Sr \in Ar(C)$. Then u is an universal arrow if and, only if, the function $\varphi : \text{hom}_D(r, \cdot) \rightarrow \text{hom}(c, S\cdot)$ such that $\varphi(d)(f) = Sf \circ u$ for all $f \in \text{hom}_D(r, d)$ is a natural bijection. Conversely, every natural bijection is uniquely determined by an universal arrow $u : c \rightarrow Sr$.

Proof. Let u be universal. Then for φ to be a natural transformation the diagram

$$\begin{array}{ccc} \text{hom}_D(r, d) & \xrightarrow{\varphi(d)} & \text{hom}_C(r, Sd) \\ \text{hom}_D(r, g) \downarrow & & \downarrow \text{hom}_C(r, Sg) \\ \text{hom}_D(r, d') & \xrightarrow{\varphi(d')} & \text{hom}_C(r, Sd') \end{array}$$

should commute for all $g \in \text{Ar}(D)$. As this is a diagram in the category of sets, we can check the commutativity by checking it element wise. For any $f \in \text{hom}_D(r, d)$:

$$\begin{array}{ccc} f & \xrightarrow{\varphi(d)} & Sf \circ u \\ \text{hom}_D(r, g) \downarrow & & \downarrow \text{hom}_C(r, Sg) \\ g \circ f & \xrightarrow{\varphi(d')} & S(g \circ f) \circ u = Sg \circ Sf \circ u \end{array}$$

So the diagram commutes, and φ is natural. The bijectivity follows from u being universal.

Lets consider now that φ is a natural bijection. We will define $u := \varphi(r)(1_r)$ and check that (r, u) is an universal arrow. As φ is natural we have that:

$$\begin{array}{ccc} \text{hom}_D(r, r) & \xrightarrow{\varphi(r)} & \text{hom}_C(r, Sr) \\ \text{hom}_D(r, g) \downarrow & & \downarrow \text{hom}_C(r, Sg) \\ \text{hom}_D(r, d) & \xrightarrow{\varphi(d)} & \text{hom}_C(r, Sd) \end{array}$$

Writing the diagram for the element $1_r \in \text{hom}_D(r, r)$ and any $d \in \text{Ob}(D)$, $g : r \rightarrow d \in \text{hom}_D(r, d)$:

$$\begin{array}{ccc} 1_r & \xrightarrow{\varphi(r)} & u \\ \text{hom}_D(r, g) \downarrow & & \downarrow \text{hom}_C(r, Sg) \\ g & \xrightarrow{\varphi(d)} & \varphi(d)(g) = Sg \circ u \end{array}$$

and since φ is a bijection, for every $f \in \text{hom}_C(r, Sd)$ there is an unique function $f' = \varphi(d)^{-1}(f)$ such that $Sf' \circ u = f$, thus being u universal. □

From this theorem there is a definition that arises:

Definition 2.1.4. Let D be a category with small home-sets and let $F : D \rightarrow C$ be a functor. A representation of a functor $K : D \rightarrow \text{Set}$ is a pair (r, φ) with $r \in \text{Ob}(D)$ and φ a natural isomorphism such that

$$D(r, \cdot) \equiv_{\varphi} F.$$

A functor is said to be *re-presentable* whenever it has a representation.

Note that therefore a universal arrow induces a natural isomorphism $D(r, d) \equiv C(c, Sd)$ and this induces a representation of the functor $C(c, S\cdot) : D \rightarrow \text{Set}$, being these three equivalent.

2.1.1 Yoneda's lemma

This subsection deals with Yoneda's Lemma. Mac Lane[22] assures the lemma first appeared in his private communication with Yoneda in 1954. With time, this result has became one of the most relevant one in Category Spaces. We will start by providing some intuition to it, followed by it proof and some use cases.

This results is due to Japanese professor Nobuo Yoneda. We know about Yoneda's life thanks to the elegy that was written by Yoshiki Kinoshita[33]. Yoneda was born in Japan in 1930, and received his doctorate in mathematics from Tokyo University in 1952. He was a reviewer for international mathematical journals. In addition to his contributions to the field of mathematics, he also devoted his research to computer science.

The idea behind the Yoneda lemma can be arid at first, if one does not have a prior understanding of what the purpose and usefulness of this lemma is. In order to illustrate this idea we will introduce a (simplified) definition of Moduli Spaces, so that we have a geometric understanding of Yoneda's Lemma.

The idea behind (some) Moduli spaces is to classify algebraic curves up to isomorphisms. In addition, Moduli spaces allow us to control complex mathematical objects (such as a quotient space of unknown objects) by simpler objects or objects with better properties (such as a concrete variety). A canonical example of this type of classification is:

$$\begin{aligned} \{\text{Vector spaces of finite dimension}\} / \text{isomorphism} &\cong \mathbb{N} \\ [V] &\rightarrow \dim V. \end{aligned}$$

Where a complex object can be classified by another object of which we know more properties. We can start by defining:

$$\mathcal{M} = \{\text{smooth complex non singular curves}\} / \text{isomorphism}$$

Further on when we talk about curves we will refer to smooth complex non singular curves. Note that if two curves are isomorphic then they have the same genus. Therefore the function

$$\begin{aligned} \gamma : \mathcal{M} &\mapsto \mathbb{N} \\ [V] &\mapsto \text{genus of } V \end{aligned}$$

is well defined and we can define $\mathcal{M}_g = \gamma^{-1}(g)$. An interesting classification of \mathcal{M}_g is given when we consider that for every g there exists a closed, connected, non-singular variety U_g and a family $\{C_t : t \in U_g\}$ such that a curve of genus g will be a fibration of C_t . Moreover there is a variety M_g and a subjective morphism $\varphi : U_g \rightarrow M_g$ such that $\varphi(t_1) = \varphi(t_2)$ if $C_{t_1} \equiv C_{t_2}$. Therefore we are classifying the equivalence classes of \mathcal{M}_g by points of the variety M_g (thus generating a Moduli problem).

Similarly to this two example, with the Yoneda lemma we will have a functor $F : D \rightarrow \text{Set}$ and one representation of this functor. We will classify the natural transformation of these functors by the set in the image of F ! Interestingly enough, there will be applications where the complex object is not the space of natural transformations, but the images of F (see 2.1.2 for an example). Lets proceed to enunciate and proof the result.

Theorem 2.1.1. [22, Section 3.2] Let D be a category with small home-sets, $F : D \rightarrow \text{Set}$ be a functor, and $r \in \text{Ob}(D)$. Then there is a bijection

$$\begin{aligned}\tau : \text{Nat}(\text{hom}_D(r, \cdot), F \cdot) &\equiv Fr \\ \tau(\alpha : \text{hom}_D(r, \cdot) \rightarrow F \cdot) &= \alpha(r)(1_r)\end{aligned}$$

Where τ is natural in K (as an object of Set^D) and in r .

Proof. As α is a natural transformation we have that, for every $g : r \rightarrow d \in \text{Ar}(D)$:

$$\begin{array}{ccc}\text{hom}_D(r, r) & \xrightarrow{\alpha(r)} & Kr \\ \text{hom}_D(r, g) \downarrow & & \downarrow Kg \\ \text{hom}_D(r, d) & \xrightarrow{\alpha(d)} & Kd\end{array}$$

Writing $\alpha(r)(1_r) = u$ we have that:

$$\begin{array}{ccc}1_r & \xrightarrow{\alpha(r)} & u \\ \text{hom}_D(r, g) \downarrow & & \downarrow Kg \\ g & \xrightarrow{\alpha(d)} & \alpha(d)(g) = Kg(u)\end{array}$$

Therefore every natural transformation is uniquely identified by the value of u , therefore τ is injective. Moreover, for every u in Kr , we can define a natural transformation following the previous diagram, therefore, τ is bijective.

To see that τ we is natural we have to consider for which functor it is natural. Consider the functor *Evaluation* $E : \text{Set}^D \times D \rightarrow \text{Set}$ that maps each $(F, c) \rightarrow Fc$, and the functor $N : \text{Set}^D \times D \rightarrow \text{Nat}(\text{hom}_D(r, \cdot), K)$ the set of natural transformations. Finally, $\tau : N \rightarrow E$ is a natural transformation. \square

The first functor that we will want to apply this result is to the hom. functor. But this functor is a bifunctor, so to get the full result of this lemma applied to the full bifunctor we may restate this lemma to contravariant functors.

Corollary 2.1.1.1. Let D be a category with small home-sets, $F : D \rightarrow \text{Set}$ be a contravariant functor, and $r \in \text{Ob}(D)$. Then there is a bijection

$$\begin{aligned}\tau : \text{Nat}(\text{hom}_D(\cdot, r), F \cdot) &\equiv Fr \\ \tau(\alpha : \text{hom}_D(\cdot, r) \rightarrow F \cdot) &= \alpha(r)(1_r)\end{aligned}$$

Where τ is natural in K (as an object of Set^D) and in r .

Proof. We seek to use the Yoneda lemma in the functor $F' : D^{op} \rightarrow \text{Set}$ induced by F . Then we have that:

$$\begin{aligned}\tau : \text{Nat}(\text{hom}_{D^{op}}(r, \cdot), F' \cdot) &\equiv F'r \\ \tau(\alpha : \text{hom}_{D^{op}}(r, \cdot) \rightarrow F' \cdot) &= \alpha(r)(1_r)\end{aligned}$$

Taking into account that $F|_{\text{Ob}(D)} = F'|_{\text{Ob}(D^{op})}$, and that $\text{hom}_{D^{op}}(r, \cdot) = \text{hom}_D(\cdot, r)$ we have the result. \square

As we have seen, the Yoneda lemma is a direct generalization of the moduli problem. In the same vein, Yoneda's lemma is the generalisation of other problems/theorems in mathematics, most notably Cayley's lemma. It states:

Proposition 2.1.2. Any group is isomorphic to a subgroup of a symmetric group.

To understand this, take a groups G seen as a single-object category, and name that object e . Then, the functor $\text{hom}_G(e, \cdot) : G \rightarrow \text{Set}$ can be seen as a group action **1.2.2**. Then the Yoneda lemma states that:

$$\text{Nat}(\text{hom}_G(e, \cdot), \text{Hom}_G(e, \cdot)) \equiv_{\varphi} \text{Hom}_G(e, e).$$

Translating this result to group theory:

- Remember that $\text{Hom}_G(e, e)$ is the group G .
- Every natural transformation is a equivariant map between G -sets.
- This equivariant maps, forms an endomorphism group under composition, being a subgroup of the group of permutations.
- This natural isomorphism φ define a group isomorphism.

So we have the isomorphism of groups that is stated in Cayley's Theorem.

We continue our exploration of Yoneda lemma by defining the *Yoneda Embedding*. For that we define the contravariant functor $h_a = \text{hom}_C(\cdot, a)$. Then the contravariant Yoneda lemma tell us that:

$$\text{Nat}(h_a, h_b) \equiv_{\tau_a} \text{hom}(a, b).$$

We then can define a fully faithful embedding $v : C \rightarrow \text{Set}^{C^{op}}$ such that

$$\begin{aligned} va &= \text{hom}_C(A, \cdot) & \forall a \in \text{Ob}(C), \\ vf &= \tau_a^{-1}(f) & \forall f : b \rightarrow a \in \text{Ar}(C). \end{aligned}$$

This functor allows us to view the category C as a subcategory of the category of contravariant functors from C to Set , which will be useful for determining "heritable" properties in C .

2.1.2 Properties expressed in terms of universality

After the examples given, we define a few constructions that are commonplace in Maths. We will outline the notions of limit, pullback and product, and the dual notions of colimit, pushout and coproduct.

The notions of product and pullback can be seen as particular cases of the notion of limit. To define limit we will introduce the concept of co-cone and the diagonal functor.

Definition 2.1.5. Let C, J be categories. We can define the functor $\Delta_J : C \rightarrow C^J$ that maps c to the functor from J to C that is constantly c , and maps every arrow to the identity 1_c .

Whenever possible we will write only Δ , and let the information of the category be deduced from context. J is usually small and often finite. We can now consider

a natural transformation $\tau : F \rightarrow \Delta c$. This can be represented as in the following diagram:

$$\begin{array}{ccc} Fx_j & \xrightarrow{Fg} & Fx_k \\ & \searrow \tau x_j & \swarrow \tau x_k \\ & c & \end{array}$$

commutes for every $g : x_j \rightarrow x_k \in Ar(j)$, for that reason, such natural transformation is usually called a co-cone. The dual notion is called cone and is represented as:

$$\begin{array}{ccc} Fx_j & \xrightarrow{Fg} & Fx_k \\ & \swarrow \tau x_j & \searrow \tau x_k \\ & c & \end{array}$$

We can now define the concepts of limit and colimit. We introduce first the concept of colimit. This definition is that of an universal arrow, only in a category of functors. Following this definition, we will define the limit as its dual concept.

Definition 2.1.6. A colimit is an object $r \in Ob(C)$ together with an universal arrow $u : F \rightarrow \Delta r \in Ar(C^J)$. The colimit is denoted by

$$\lim_{\leftarrow} F = r = \text{colim } F.$$

The notation \lim_{\leftarrow} is intuitive: in the colimit we have arrows to F . To represent this as a diagram, we have a co-cone $u \rightarrow \text{colim } F$ such that for every other co-cone $\tau \rightarrow s$, it exist an unique f such that the following commutes for every $x_j, x_k \in Ob(C)$:

$$\begin{array}{ccc} & l & \\ \tau x_j \nearrow & \uparrow f & \nwarrow \tau x_k \\ & \text{colim } F & \\ u x_j \nearrow & \downarrow u & \nwarrow u x_k \\ x_j & \xrightarrow{Fg} & x_k \end{array}$$

Now, thanks to the duality of categories, we can define what a limit is in a very synthetic way:

Definition 2.1.7. A limit is the dual concept of a colimit. It is denoted as

$$\lim_{\rightarrow} F = r = \lim F.$$

A limit is represented by the following diagram:

$$\begin{array}{ccc} & l & \\ \tau x_j \nwarrow & \downarrow f & \swarrow \tau x_j \\ & \lim F & \\ u x_j \nwarrow & \uparrow u & \swarrow u x_k \\ x_j & \xrightarrow{Fg} & x_k \end{array}$$

Analogously as in the colimit notation, in the limit we have arrows from F , and thus the notation \lim_{\rightarrow} . Let focus for a while now in the notion of limit, in particular of two of its special cases: the product and the pullback. From these cases we are going to provide most examples.

We have already talked about the product of categories. The product is a limit where J is the 2-element discrete category, that is, where every functor $F : J \rightarrow C$ is merely choosing to object of C .

Definition 2.1.8. Let C be a category, $J = \{0, 1\}$ be the discrete category with two elements. The product $c_1 \times c_2$ of two elements $c_0, c_1 \in Ob(C)$ is the limit of the functor $F : J \rightarrow C$ such that $F0 = c_0, F1 = c_1$.

This construction means that providing an arrow to c_0, c_1 determines an unique arrow to $c_0 \times c_1$ and vice versa by composition with π_i . In this case, the arrows u_0, u_1 are usually called *projections* and denoted by π_0, π_1 . The notation is due to the product being a generalization of the Cartesian product in the category *Set*. It is also sometimes note with $c_0 \Pi c_1$ with Π being standard for the sequence product. Some examples of product object in categories are:

Example 2.1.3.

- Products from Example 2.1.2.
- In Haskell, considering two integer types A and B , we can consider the duple type (A, B) that is the product, along with projections fst and snd to be a product. We can fairly easily check that, for any other integer type C and any morphism $f : C \rightarrow (A, B)$ it exist a unique g and h such that:

$$\begin{array}{ccccc}
 & & C & & \\
 & \swarrow g & \downarrow f & \searrow h & \\
 A & \xleftarrow{fst} & (A, B) & \xrightarrow{snd} & B
 \end{array}$$

Note that we have requested A and B to be integer types. Quite surprisingly, this construction can not be generalized in Haskell to provide a product type for every object[12]. This will provide in the future a palpable difference between our theoretical λ -calculus, and its applicable version, Haskell.

This troubles arise from of implementation details of bottom values. Why have not anyone fix this? Well, when functions have to terminate and only finite values are considered this problems does not Arise. This condition is fairly acceptable in any engineering scenario.

Analogously, we can define the coproduct, on which instead of defining an arrow to c_0, c_1 , we define an object *from* c_0, c_1 .

Definition 2.1.9. The coproduct is the dual definition of the product. It is denoted by $c_0 \sqcup c_1$.

In this notation \sqcup denotes an inverted Π , with the meaning of being the dual notion of the product.

Example 2.1.4.

- In the category Ab of Abelian Group and morphism, finite products and coproducts are equivalent. This equivalence also happens in others categories, such as R -Modules for a ring R or vector spaces. This has a underlying idea of a type of category that relates this constructions: This are all *Abelian Categories*, as in [27, Section 5.5].

We will not delve further into this concept so as not to deviate from the subject at hand. However, for those readers who are familiar with the notation, we cannot resist including Mitchell's theorem[25, Chapter IV] .

Theorem 2.1.2 (Mitchell's Theorem). *If A is a small abelian category, then there is a covariant full faithful exact functor $F : A \rightarrow Ab$.*

As a consequence, any statement " p implies q " where p and q are categorical statmenet about a diagram in A , if is true in Ab , it holds true in A .

After learning about the product and the coproduct, we will focus now in the notion of pullback and its dual, the pushout. We will first define the category

$$P = x \xrightarrow{f} z \xleftarrow{g} y$$

Then we can define the pullback:

Definition 2.1.10. Let C be a category and $F : P \rightarrow C$ be a functor. Then the pullback of Fx and Fy denoted as $Fx \times_{Fz} Fy$ is the limit of the functor F .

We can represent this structure in the following diagram. For any object q and arrows $f' : q \rightarrow Fx$, $g' : q \rightarrow Fy$ we have:

$$\begin{array}{ccccc}
 q & & & & \\
 & \searrow^{g'} & & & \\
 & & Fx \times_{Fz} Fy & \xrightarrow{p_2} & Fy \\
 & \searrow^{u} & & & \downarrow Fg \\
 & & Fx & \xrightarrow{Ff} & Fz \\
 & \searrow^{f'} & & & \\
 & & & &
 \end{array}$$

Analogously, we can define:

$$CoP = x \xleftarrow{f} z \xrightarrow{g} y$$

and define:

Definition 2.1.11. Let C be a category and $F : CoP \rightarrow C$ be a functor. Then the pushout of Fx and Fy denoted as $Fx \sqcup_{Fz} Fy$ is the colimit of the functor F .

Example 2.1.5. • Let $A, B, C \in Ob(Set)$, and let $f : C \rightarrow A, g : C \rightarrow B \in Ar(Set)$. The pushout of f and g is the disjoint union of X and Y , where elements sharing a common preimage (in Z).

- Fiber Product: The fiber product is the canonical pullback of
- Seifert-Van-Kampen (Si tienes valor).

Note the similarity of the pullback/pushout and the one of product/coproduct notation-wise. To understand these we have to consider the similarities of both construction. We are going to focus on the similarities of product and pullback, letting

the coproduct/pushouts as duals.

In both case, the universal property consists of having an arrow to a generated object only if we have an arrow to each of its generators. In this line of reasoning, we can consider that the product is a pullback where we forget about the object z and its arrows. One easy way to generate that case is to consider the construction when Fz is a terminal object. In that case we have that the existence of Ff and Fg is a tautology, and we can consider

$$\begin{array}{ccccc}
 & q_1 & q & q_2 & \\
 & \curvearrowright & \downarrow u & \curvearrowleft & \\
 Fx & \xleftarrow{\pi_0} & Fx \times_{Fz} Fy & \xrightarrow{\pi_1} & Fy
 \end{array}$$

2.2 Adjoints

Adjointness is a fundamental theory within Category theory. It relates the homesets of two functors $F : C \rightarrow D, G : D \rightarrow C$. The importance of adjoints however, comes from its ubiquity among mathematics, often relate with the ubiquity of universality. This notion was first presented by Daniel M. Kan in [17]. For this section we follow the material presented in [22].

We will start by providing some intuitive notions, before a formal definition. Take the Forgetful Functor $U : Grp \rightarrow Set$, and the Free Group Functor $\mathcal{F} : Set \rightarrow Grp$. We can see that it is not difficult to consider that we can compose F and G to make endofunctors. These endofunctors are far from being identities, nonetheless we have still a great relation between them: for every set X and group G , there is a function $f : X \rightarrow UG$ for each morphism $g : FX \rightarrow U$. Conversely, any function from X to UG induces a morphism.

Any avid reader will detect by this point the taste of universality. But there is a bit more, we have a bijective relation on every image home-set of both F and G . This is the underlying property of adjointness - to relate home-sets. Lets formalize this idea:

Definition 2.2.1. Let C, D be categories. And adjunction is a triple $(F, G, \varphi) : D \rightarrow C$ where F, G are functors:

$$D \begin{array}{c} \xrightarrow{G} \\ \xleftarrow{F} \end{array} C$$

while φ is a transformation that maps each $(c, d) \in Ob(C \times D)$ with a bijection:

$$\varphi_{c,d} : \text{hom}_C(Fd, c) \equiv \text{hom}_D(d, Gc).$$

which is natural in c and d .

We have a bit to unpack in this definition. We will start to understand in what sense φ is natural. Remembering about N functor in Yoneda's Lemma, we can see that it is natural bijection from $\varphi : \text{Hom}_C(F \cdot, \cdot) \rightarrow \text{hom}_D(\cdot, G \cdot)$ in each variable. That is, for every $f : d \rightarrow d' \in C, k : c \rightarrow c' \in D$ the diagrams

$$\begin{array}{ccc}
\text{hom}_C(Fd, c) & \xrightarrow{\varphi_{c,d}} & \text{hom}_D(d, Gc) & \quad & \text{hom}_C(Fd, c) & \xrightarrow{\varphi_{c,d}} & \text{hom}_D(d, Gc) \\
\downarrow \text{hom}_C(Fd, \cdot)(g) & & \downarrow \text{hom}_D(d, G\cdot)(g) & & \downarrow \text{hom}_C(F\cdot, c)(f) & & \downarrow \text{hom}_D(\cdot, Gc)(f) \\
\text{hom}_C(Fd, c') & \xrightarrow{\varphi_{c',d}} & \text{hom}_D(d, Gc') & \quad & \text{hom}_C(Fd, c') & \xrightarrow{\varphi_{c,d'}} & \text{hom}_D(d, Gc')
\end{array}$$

commutes.

We can follow by considering the important notation decision: how to call the adjoints. This is a quite ambiguous notation, but we will stick with the notation of F being the *left adjoint* and G being the *right adjoint*. When a functor *is* a left (resp. right) adjoint it *has* a right (resp. left) adjoint. This notation comes from where is the functor placed in the home-set, when making the bijection.

We have already suggested the relationship between universality and adjointness. We can summary that relation in the following property:

Proposition 2.2.1. An adjunction $(F, G, \varphi) : D \rightarrow C$ determines:

- a natural transformation $\eta : I_D \rightarrow GF$ such that $\eta(d) : d \rightarrow GFd$ is universal to G from d for every $d \in \text{Ob}(D)$. Conversely, we can define:

$$\varphi(f : Fd \rightarrow c) = Gf \circ \eta(d) : d \rightarrow Gc.$$

- a natural transformation $\epsilon : FG \rightarrow I_C$ such that $\epsilon(c) : FGc \rightarrow c$ is universal from c to F and we can define:

$$\varphi(g : d \rightarrow Gc) = \epsilon(c) \circ Fg : Fd \rightarrow c.$$

Proof. • Let $a = Fd$, then we have that

$$\text{hom}_C(a, c) \equiv \text{hom}_D(d, Gc).$$

and by proposition 2.1.1 we have an universal arrow $\eta(d) : d \rightarrow Ga = GFd$ is provided. The function $d \rightarrow \eta(d)$ is natural $I_D \rightarrow GF$ as:

$$\begin{array}{ccc}
d & \xrightarrow{\eta^c} & GFd \\
\downarrow h & & \downarrow GFh \\
d' & \xrightarrow{\eta^{c'}} & GFd'
\end{array}$$

commutes.

- Analogous.

□

From this proposition we can see that we may be able to define an adjoint based only on the universal arrows provided. We can summary a few equivalent definition of adjoint:

Proposition 2.2.2. Each adjoint $(F, G, \varphi, \eta, \epsilon) : D \rightarrow C$ is completely determined by the items in any one of the following list:

1. F, G and a natural transformation $\eta : 1_D \rightarrow GF$ such that $\eta(d)$ is universal for every $d \in (D)$.
2. F, G and a natural transformation $\varepsilon : FG \rightarrow 1_C$ such that $\varepsilon(c)$ is universal for every $c \in (C)$.
3. G and for each $d \in Ob(D)$:
 - an object $F_0(d) \in Ob(C)$.
 - an universal arrow $v(x) : d \rightarrow GF_0d$.
 Then F has F_0 as object function and $F(h : d \rightarrow d') = \eta(x') \circ h$.
4. F and for each $c \in Ob(C)$:
 - an object $G_0(c) \in Ob(D)$.
 - an universal arrow $\varepsilon(c) : c \rightarrow GF_0c$.
5. F, G and two natural transformation $\eta : I_D \rightarrow GF, \varepsilon : FG \rightarrow I_C$ such that both composites are identities.

Proof. 1. We need to define the natural bijection $\varphi : C(Fd, c) \rightarrow D(d, Gc)$. Defining $\varphi(g) = Gg \circ \eta(c)$ for each $g : Fd \rightarrow c$. Is is well define as $Gg \circ \eta(c) : d \rightarrow Gc$ and it is a bijection due to $\eta(x)$ universality.

It is natural in d because η is natural and is natural in c because G s a functor.

2. Dual of the previous.
3. We will proof that there is only one functor with F_0 as object function such that $\eta(x) : I_D \rightarrow GF$ is natural. The naturality and universality told us that each $h : d \rightarrow d' \in Ob(D)$ induces two arrows:

$$\begin{array}{ccccc}
 F_0d & & d & \xrightarrow{\eta(d)} & GF_0d \\
 \vdots & & \downarrow h & & \vdots \\
 F_0d' & & d' & \xrightarrow{\eta(d')} & GF_0d'
 \end{array}$$

So the only way to define $Fh = \eta(x) \circ h$. We conclude applying 1.

4. Dual of the previous.

□

To further illustrate this concept we present some examples:

Example 2.2.1. • Free category from a graph and forgetful functor
 • Čech compactification.

TODO? Lastly, we are going to study the and prove a theorem that allow us to include parameters in adjoints.

2.2.1 Equivalence of Categories

We can define an isomorphism of categories the same way that we define isomorphisms in any other category: an isomorphism is an arrow (Functor) with a two sided inverse. This definition, while standard, is quite restrictive. We are going to need some more lax concept of equivalence of categories, in the sense that while not being exactly the same, they are mostly the same. Formally:

Definition 2.2.2. A functor $F : C \rightarrow D$ is an equivalence of categories if there exists a functor $G : D \rightarrow C$ and two natural isomorphisms $\varphi : I_C \rightarrow GF$ and $\zeta : I_D \rightarrow FG$

For the canonical example we may introduce a really organic concept: the *skeleton* of a category. Quite often in mathematics we do not consider all objects of certain type, but rather objects up to isomorphism. The skeleton category of a category C is another category where we consider the objects up to isomorphism. Formally:

Definition 2.2.3. Let C be a category. The skeleton of C , namely $ske(C)$, is a subcategory such that every object in C is isomorphic to an object in $ske(C)$.

The definition of equivalence of categories previously outline will allow us, for example, to consider $C \sim ske(C)$, while not being isomorphic. Continuing our discussion, it is not difficult to draw similarities between equivalences and adjoints. That motivates the further definition:

Definition 2.2.4. Let $(F, G, \varphi, \eta, \varepsilon)$ be an adjoint. It is called an *adjoint equivalence* whenever η and ε are natural equivalences.

It is clear that every adjoint equivalence induces two equivalences in F and G . We state this idea in the following proposition:

Proposition 2.2.3. [22, Theorem 1, 4.4] Let $F : C \rightarrow D$ be a functor. Then the following properties are equivalent:

- i) F is an equivalence of categories.
- ii) F is part of an adjoint equivalence.
- iii) F is full and faithful, and each object $c \in C$ is isomorphic to Sa for some object $a \in A$.

Proof.

- ii) \implies i) Given an equivalent adjoint $(F, G, \varphi, \eta, \varepsilon)$, then F is an equivalence with G, η, ε .
- i) \implies iii) $\varphi : GF \equiv I_C$ implies that for every $c \in Ob(C)$ we can consider $c \equiv GFc$. Then considering the natural isomorphism $\zeta : FG \equiv I_D$ states for every $f : a \rightarrow a' \in D$

$$\begin{array}{ccc} FGa & \xleftarrow{\zeta^{-1}a} & a \\ \downarrow FGf & & \downarrow f \\ FGa' & \xrightarrow{\zeta a'} & a' \end{array}$$

there is one FGf for each f and we get that G is faithful. Analogously we can see that F is also faithful. To see that G is full we can

- iii) \implies ii) We can see that

□

In the next few subsection, we are going to introduce categories, with some additional structures onto them. This type of considerations, are commonplace in category theory, and will provide useful considerations.

2.2.2 Monad

2.2.3 Closed Cartesian Categories

The notion of product seen in 2.1.8 is a notion that seek to catch the essence of what the Cartesian product is in the category of Set . In this category it happens that for any two objects, one can consider the product without any hesitation about its existence. A *Cartesian category* will be a category that, in some sense, maintain this property (of being closed under Cartesian product). Formally:

Definition 2.2.5. A Cartesian category is a category with a distinguished terminal object T and for which every finite product exists.

Nonetheless, further on the text we will need categories with some even nicer properties. These categories are called *closed cartesian categories*. We will define them formally first, and after unpack the information that the definition contains:

Definition 2.2.6. A C is closed cartesian if each of the following functors:

$$\begin{array}{lll} F_1 : C \rightarrow 1 & F_2 = \Delta : C \rightarrow C \times C & F_3^b : C \rightarrow C \\ c \rightarrow e & c \rightarrow (c, c) & c \rightarrow c \times b \end{array}$$

has a *specified* right adjoint, denoted by:

$$\begin{array}{lll} G_1 : 1 \rightarrow C & G_2 : C \times C \rightarrow C & G_3^b : C \rightarrow C \\ e \rightarrow t & (c, b) \rightarrow c \times b & c \rightarrow c^b \end{array}$$

These adjoints provide us with a lot of information:

- From F_1 being an adjoint we get that t is terminal as for every $c \in \text{Ob}(C)$:

$$\{id_e\} \equiv \text{hom}_1(F_1(c), e) \equiv \text{hom}_C(c, Ge = t)$$

- From F_2 we get that every pair c, b has a product as it states the universal property of product:

$$\text{hom}_{C \times C}(F_2(c), (c', b')) \equiv \text{hom}_{C \times C}((c, c), (c', b')) \equiv \text{hom}_C(c, c' \times b')$$

that is, for every object in $c \in C$, to provide a morphism to $c \rightarrow c' \times b'$ is the same as providing morphisms $c \rightarrow c', c \rightarrow b'$.

- First of all, as every product exists, and it is specified by F_2 , we can define F_3^b for every b . Then, its adjointness states that:

$$\text{hom}_C(c \times b, d) \equiv \text{hom}_C(c, d^b)$$

This object d^b is called the exponential object or map object. The intuitive notion is that this object represents in some way the arrows from b to c , being a generalization of the function set of two small sets. The best way to understand this adjoint is by the natural transformation $\varepsilon^b(c^b \times b) = c$. In this context, this is called *evaluation arrow*. In the context of Set this amounts to the classic evaluation of a function.

actually it is a technical condition that this adjoint is natural in b (cita macLane).

Cartesian Closed Categories will be reformulated in Chapter 4, proposition 4.1.2. We will use these last ideas in order to equationally present the concept. For now on, let's provide some examples of Cartesian Closed Categories:

Example 2.2.2. • *Set*

- The category of compactly generated Hausdorff spaces.
- We will prove later that lambda calculus is, in some sense, a closed cartesian category.

Proposition 4.1 Lambeck: **TODO** .

Part II

Lambda Calculus

Chapter 3

Lambda Calculus

In this chapter we define the lambda calculus as a formal language of computation, and on this define the concept of typing, ubiquitous in programming languages. We will carry out this project raising as many bridges between category theory and the lambda calculus as possible.

The main references for this chapter are [29] for the general approach and concepts relatives to untyped calculus, [21] for more specifics details and the category theory approach to the calculus. We refer to [3] to further understand the historical motivation for the development of the theory.

One of the important advances in 19th century mathematics is the development of the concept of function. However, what makes two functions the same? The most widespread view is the *extensional* approach. In this, we consider two functions to be the same if for the same input they have the same output. In this case, the functions exist by themselves, and each f as a pairing of an X domain to an Y codomain. These functions can be considered as sets $f \subset X \times Y$.

Despite that, specially those involved in computing the functions, can consider this notion of equality misleading. For example, consider a prime p big enough, and let f and g be two endomorphisms of $\mathbb{Z}/p\mathbb{Z}$. One could argue that the endomorphism of $f(x) \rightarrow x^2$ is different to $g(x) \rightarrow \log_a a^{x+2}$. Despite having the same output for the same input, one is clearly different in complexity. It even involve the resolution of a discrete logarithm, that is highly non trivial.

This view, in which not only is the result of the function important but how is that result obtained, is called the *intensional* approach. This approach, gain traction in early 1930 as Church[5], Gödel[1] or Turing[31] start formalizing what is to be computable. This approach is now as ubiquitous modern computer program care not only on the correctness of a program, but on its time and space complexity (to the point on which correctness is often partially dropped to easy time complexity, for example [15]).

In lambda calculus we consider function as formulas, and thus, we consider an intensional approach. This intensional approach was also backed by the constructivist, to whom we will later on relate with the study of the Curry-Howard isomorphism [16].

3.1 Untyped Lambda Calculus

We will start defining the most simple version of lambda calculus: untyped lambda calculus. Let's define some concepts:

1. An alphabet A is an arbitrary, maybe finite, non-empty set.
2. A symbol a is an element of the alphabet.
3. A word/formula is a finite sequence of symbols.
4. The collection of all possible words over an alphabet A is denoted by A^* .
5. A language L over A is a subset of A^* .

There are a lot of languages. For example, Spanish is a language, with a well-known alphabet L , with a proper subset of words over L^* . In the same fashion, we define lambda calculus as a formal language, defining its syntax, that is, what words are valid. After that, we will provide the semantics of the language, that is, we will provide meaning to the words.

Syntax of untyped λ -calculus

We start with the basic building blocks, which collectively form what is called the alphabet:

- We denote x, y, z, \dots for variables. As more variables are necessary sub-indexes will be used, up to countable infinite variables.
- We consider an abstractor connector λ .

Now, we are ready to formally define the untyped λ -calculus:

Definition 3.1.1 (Syntax of Untyped λ -calculus (section 2.1 [29])). A λ -calculus formula (sometimes called term) is defined inductively:

- Every variable x, y, z, \dots is a valid formula.
- If A, B is a formula, then AB is a valid formula.
- If A is a formula and x is a variable, then $\lambda x.M$ is a valid formula.

The set of all variables is denoted by \mathcal{V} and the set of all λ -formulas is denoted by Λ .

Dealing with formal languages, more often than not, we make use of similar inductive statements. Because of this, we find it useful to introduce the Backus-Naur Form notation, noted as BNF [19]. A BNF specification is a set of derivation rules, written as

$$\text{symbols} ::= \text{expression1} \mid \text{expression2} \mid \dots,$$

where symbol is a valid word, and each expression consists of a derived valid formulas. Expressions are separated by the vertical bar $|$. For example, we can revisit definition 3.1.1 as follow:

Definition 3.1.2. The formulas of λ -calculus are built via the BNF:

$$A, B ::= x \mid (AB) \mid (\lambda x.A).$$

where x denote any variable.

From this point on we know how the λ -formulas look like. Now it is time to provide meaning. This point is better understood with some examples, using natural numbers. We recommend to trust us in their existence and read this examples first to gain traction in the system. The notion of natural numbers is formalized definition 3.1.16.

Semantics of untyped λ -calculus

Let us now explain the idea behind the formalism. Consider the expression $\lambda x.(x + 1)$. This expression represent the idea of the function $f(x) = x + 1$ that take a variable x and return $x + 1$. $\lambda x.M$ is called the *abstraction* of x .

From the notion of abstraction naturally arises the second one: *application*. Consider formulas $M = \lambda x.x + 1$ and $N = 3$. Then $MN = (\lambda x.x + 1)(3)$ represent the application of M to N . In untyped λ -calculus, N can be any formula. Thus for example, the formula $\lambda f.\lambda g.fg$ just represent the composition of formulas.

Example 3.1.1. The formula

$$\lambda g.(\lambda f.(\lambda x.(gf)(x)))(x + 1)(x + 2),$$

can be understood as $(g \circ f)(x)$ where $g(x) = x + 1$ and $f(x) = x + 2$.

In a expression $M = (\lambda x.N)$ we say that the variable x is *bound* in M .

This notion however has to be formalized. This is done via the notions of α -equivalence, β -equivalence and η -equivalence.

The idea of α -equivalence, $=_\alpha$, is that expressions such as $\lambda x.x$ and $\lambda y.y$ are essentially the same. That is, we consider formulas up to rename of variables. To formalise this, we have to formalize the concept of free and bound variables, and the concept of renamed.

Definition 3.1.3. We have a function $FV : \Lambda \rightarrow \mathcal{P}(\mathcal{V})$ defined recursively, such that:

- $FV(x) = \{x\}$ for every $x \in \mathcal{V}$.
- $FV(MN) = FV(M) \cup FV(N)$ for every $M, N \in \Lambda$.
- $FV(\lambda x.M) = FV(M) \setminus \{x\}$ for every $M \in \Lambda, x \in \mathcal{V}$.

We can now define the rename of a variable. We are going to define the more general process of substitution, and define renaming as a particular case. This process is the one behind the intuitive idea of evaluation. For example when we consider $(\lambda y.y^2 + y)(4) = 4^2 + 4 = 20$ we are replacing the value of x by the formula 4.

Definition 3.1.4. The substitution of N for free occurrences of x in M , denoted as $M[N/x]$ is defined recurrently in the structure of λ -formulas by:

$$\begin{aligned}
 x[N/x] &\equiv N, \\
 y[N/x] &\equiv y, & \text{if } x \neq y, \\
 (MP)[N/x] &\equiv (M[N/x])(P[N/x]), \\
 (\lambda x.M)[N/x] &\equiv \lambda x.M, \\
 (\lambda y.M)[N/x] &\equiv \lambda y.(M[N/x]), & \text{if } x \neq y \text{ and } y \notin FV(N), \\
 (\lambda y.M)[N/x] &\equiv \lambda y'.((M[y'/y])[N/x]), & \text{if } x \neq y \text{ and } y \in FV(N), \\
 & & \text{with } y' \notin FV(N) \cup \{x\}.
 \end{aligned}$$

When $N = y$ a variable we say that $[N/x] = [y/x]$ is a rename.

Definition 3.1.5. We define the α -equivalence $=_\alpha$ as the smallest congruence relation on Λ such that:

$$\lambda x.M =_\alpha \lambda y.M[x/y], \quad \forall y \in \mathcal{V} \setminus FV(M).$$

In other words is the congruence that consider every rename of a bounded variable as equals. This type of property-oriented definition is commonplace in λ -calculus, as it allows for some synthetic and goal-oriented definition. More often than note we will not give explicit use of this equivalence.

Using this same tool we are going to define the β -reduction. This is not going to be an equivalence implication, but rather a relationship. It abstracts the notion of 4 and $(\lambda x.2 + x)(2)$ being equals. Formally:

Definition 3.1.6 (Section 2.5 [29]). We define the *single-step β -reduction* as the smallest relationship \rightarrow_β such that:¹

$$\begin{aligned}
 (\beta) \quad & \overline{(\lambda x.M)N \rightarrow_\beta M[N/x]}, \\
 (\text{cong}_1) \quad & \frac{M \rightarrow_\beta M'}{MN \rightarrow_\beta M'N'}, \\
 (\text{cong}_2) \quad & \frac{N \rightarrow_\beta N'}{MN \rightarrow_\beta MN'}, \\
 (\zeta) \quad & \frac{M \rightarrow_\beta M'}{(\lambda x.M) \rightarrow_\beta \lambda x.M'}.
 \end{aligned}$$

In this definition we can see that rule (β) is the main objective, while the others are sanitary conditions.

Definition 3.1.7. We define the *multiple-step β -reduction* \twoheadrightarrow_β as the reflexive, transitive closure of \rightarrow_β .

Definition 3.1.8. We define the β -equivalence $=_\beta$ as the symmetric closure of \twoheadrightarrow_β .

While most constructions will be understood clearly using only β -reduction, we have to define the concept of η -reduction for a full picture of the system.

¹Should i explain the notation $\frac{A}{B}$

Up to this point the focus of the system was to define an intensional language for computation. The η -equivalence provides us with the tools to consider λ -calculus in an extensional way.

Definition 3.1.9. We define the single-step η -reduction \rightarrow_η as the smallest relationship such that:

$$\begin{array}{ll}
 (\eta) & \overline{(\lambda x.Mx) \rightarrow_\eta M} \quad \forall x \notin FV(M), \\
 (\text{cong}_1) & \frac{M \rightarrow_\eta M'}{MN \rightarrow_\eta M'N'} \\
 (\text{cong}_2) & \frac{N \rightarrow_\eta N'}{MN \rightarrow_\eta MN'} \\
 (\zeta) & \frac{M \rightarrow_\eta M'}{(\lambda x.M) \rightarrow_\eta \lambda x.M'}.
 \end{array}$$

Similarly, we define the multiple-step η -reduction \twoheadrightarrow_η as the transitive reflexive closure of \rightarrow_η , and the η -equivalence as the symmetric closure of \twoheadrightarrow_η .

Definition 3.1.10. We define the single-step $\beta\eta$ -reduction $\rightarrow_{\beta\eta}$ as the union of \rightarrow_β and \rightarrow_η . We define the multiple-step $\beta\eta$ -reduction $\twoheadrightarrow_{\beta\eta}$ as the transitive reflexive closure of $\rightarrow_{\beta\eta}$.

3.1.1 Church-Rosser Theorem

This subsection we present an important result for lambda calculus: the *Church-Rosser* theorem. The idea behind this theorem is to prove that every reduction (either β , η or a mix) provide an unified sense of reduction. First, we present some definitions.

Definition 3.1.11. Consider a relation \rightarrow and let \twoheadrightarrow be its reflexive transitive closure. We can define three relations:

1. The Church-Rosser Property:

$$M \twoheadrightarrow N, M \twoheadrightarrow P \implies \exists Z : N \twoheadrightarrow Z, P \twoheadrightarrow Z.$$

2. The Quasidiamond Property:

$$M \rightarrow N, M \rightarrow P \implies \exists Z : N \rightarrow Z, P \rightarrow Z.$$

3. The Diamond Property :

$$M \rightarrow N, M \rightarrow P \implies \exists Z : N \rightarrow Z, P \rightarrow Z.$$

Remark 3.1.1. Note that, while $3) \implies 1)$, it is not necessary that $2) \implies 1)$.

With this notation, we introduce the Church-Rosser Theorem, proved as done by Martin-Löf. We are going to need some tools. The first one is going to be an alternative definition of $\beta\eta$.

Definition 3.1.12 (parallel one-step reduction). We define the parallel one-step reduction \triangleright as the smallest relationship such that,

- $$\begin{array}{ll}
(1) & \overline{x \triangleright x} \\
(2) & \frac{M \triangleright M' \quad N \triangleright N'}{MN \triangleright M'N'} \\
(3) & \frac{M \triangleright M'}{(\lambda x.M) \triangleright \lambda x.M'} \\
(4) & \frac{M \triangleright M' \quad N \triangleright N'}{(\lambda x.M)N \triangleright M'[N'/x]} \\
(5) & \frac{M \triangleright M'}{(\lambda x.Mx) \triangleright M'} \quad \forall x \notin FV(M)
\end{array}$$

where x is any variable and M, N, M', N' any formula.

Lemma 3.1.1 (Characterization of \triangleright). *Let M, M' be formulas, then:*

1. $M \rightarrow_{\beta\eta} M' \implies M \triangleright M'$
2. $M \triangleright M' \implies M \rightarrow_{\beta\eta} M'$

Proof. 1. Using (1), (2) and (3) in an induction argument derives in $N \triangleright N$ for any formula. Then, we assume that $M \rightarrow_{\beta\eta} M'$. We apply induction on the structure of $\rightarrow_{\beta\eta}$ and conclude proving that every rule use for $\rightarrow_{\beta\eta} M'$ implies $M \triangleright M'$.

(β) In this case, then $M = (\lambda x.Q)M$ and $M' = Q[N'/x]$. Then using (4) $M \triangleright M'$.

(η) In this case, then $M = (\lambda x.Qx)$ and $M' = Q$. Then using (5) $M \triangleright M'$.

(cong_1) In this case, then $M = PQ$ and $M' = PQ'$ for some $Q \rightarrow_{\beta\eta} Q'$. Using induction $Q \triangleright Q'$ and using (5) $M \triangleright M'$.

(cong_2) Analogous.

(ζ) In this case, then $M = \lambda x.Q$ and $M' = \lambda x.Q'$ for some $Q \rightarrow_{\beta\eta} Q'$. Using induction $Q \triangleright Q'$ and using (3) $M \triangleright M'$.

Where, in every point, x denote some variable, and M, N, M', N', P, Q, Q' denote some formula.

2. Similarly, every possible in which $M \triangleright M'$ rule derive in $M \rightarrow_{\beta\eta} M'$:

- (1) By reflexivity of $\rightarrow_{\beta\eta}$.
- (2) By $\text{cong}_1, \text{cong}_2$ in either definition of \rightarrow_{β} and \rightarrow_{η} .
- (3) By ζ in either definition of \rightarrow_{β} and \rightarrow_{η} .
- (4) Then we have $(\lambda x.M)N \triangleright M'[N'/x]$ with $M \triangleright M' \quad N \triangleright N'$. By induction $M \rightarrow_{\beta\eta} M'$ and $N \rightarrow_{\beta\eta} N'$. By transitive closure:

$$(\lambda x.M)N \rightarrow_{\beta\eta} (\lambda x.M')N \rightarrow_{\beta\eta} (\lambda x.M')N' \rightarrow_{\beta\eta} (M')[N'/x].$$

- (5) Then we have $(\lambda x.Mx) \triangleright M'$, for some $M \triangleright M'$ and for some $x \notin FV(M)$. Finish using (cong_2) and η .

Where, in every point, x denote some variable, and M, N, M', N', P, Q, Q' denote some formula. \square

Remark 3.1.2. As a consequence, $\rightarrow_{\beta\eta}$ is the reflexive, transitive closure of \triangleright .

Lemma 3.1.2 (Substitution Lemma). *If $M \triangleright M'$ and $U \triangleright U'$, then $M[U/y] \triangleright M'[U'/y]$.*

Proof. As we define in 3.1.4 a capture-avoiding substitution, in the sense that we do not let bound variable to be substituted, we can assume without any loss of generality that M . Similarly to previous lemma, we proceed by induction, studying the last rule applied. The induction is proceed on the rules applied to $M \triangleright M'$.

- (1) In this case $M = M' = x$. If $x \neq y$ the substitution does not alter M so we have finished. If $x = y$, the formula is only $U \triangleright U'$, that we know by hypothesis.
- (2) In this case $M = NP, M' = P'N'$ for some formulas N, N', P, P' such that $N \triangleright N', P \triangleright P'$. Proceed by induction on these implications and apply (2).
- (3) In this case $M = \lambda x.N$ and $M = \lambda x.N'$, for some $N \triangleright N'$. Apply induction on N and end by (3).
- (4) Then we have $(\lambda x.M)N \triangleright M'[N'/x]$ with $M \triangleright M'$ and $N \triangleright N'$. By induction on both of the relationship, and applying (4).
- (5) Then we have $(\lambda x.Mx) \triangleright M'$, for some $M \triangleright M'$ and for some $x \notin FV(M)$. Finish using induction on $M \triangleright M'$ and by (5).

□

While the proof is rather straight forward, one can see that it does require induction, and thus the length of it.²

Definition 3.1.13 (Maximal parallel one-step reduction). Given a formula M , the *maximal parallel one-step reduction* M^* is defined inductively:

- $(x)^* = x$
- $(PN)^* = P^*N^*$ but for β -reductions.
- $((\lambda x.P)N)^* = Q^*[N/x]$
- $(\lambda x.N)^* = \lambda x.N^*$ but for η -reductions,
- $(\lambda x.Nx)^* = N^*$

where x is any variable, and N, P is any formula.

Lemma 3.1.3 (Maximal Parallel one-step). *If $M \triangleright M'$ then $M' \triangleright M^*$.*

Proof. We proceed by induction on M again:

- (1) In this case $M = M' = x$. Then $M^* = x$.
- (2) In this case $M = NP, M' = P'N'$ for some formulas N, N', P, P' such that $N \triangleright N', P \triangleright P'$.
 - If NP is not a β -reduction, then $M^* = P^*N^*$ and we can use the hypothesis induction on N^* and P^* and (2).
 - If NP is a β -reduction, then $N = \lambda x.Q$, thus $M^* = Q^*[N^*/x]$. $P = \lambda x.Q$ and $P \triangleright P'$ could be derived using congruence to λ -abstraction (2) or extensionality (5). In the first case use induction on Q and (4). On the second case $Q = Rx$, use induction on R , and apply substitution lemma.

Proceed by induction on these implications and apply (2).

- (3) In this case $M = \lambda x.N$ and $M = \lambda x.N'$, for some $N \triangleright N'$. If M is not an η -reduction, then use induction hypothesis and finish with (3). Otherwise we have that $N = Py$, and distinguish two cases on the last rule applied to N :

²Maybe add some explanation here.

- (2)→ (3) Then apply induction hypothesis to P and end using (5).
 (4)→ (3) We have that $N = P = \lambda y.Q \triangleright N' = Q'[x/y]$. Apply induction hypothesis using that $M' = \lambda x.N' = \lambda x.Q'[x/y] = \lambda y.Q'$.
 (4) Then we have $(\lambda x.P)N \triangleright P'[N'/x]$ with $P \triangleright P'$ and $P \triangleright P'$. By substitution lemma.
 (5) Then we have $(\lambda x.Px) \triangleright P'$, for some $P \triangleright P'$ and for some $x \notin FV(P)$. Finish using induction on

□

Remark 3.1.3. We have thus proved that \triangleright have the diamond property.

Remark 3.1.4. If a relation \rightarrow satisfy the diamond property, its closure \rightarrow^* satisfy the Church-Rosser property.

As a direct consequence of the previous lemmas, we prove the Church-Rosser theorem.

Theorem 3.1.4. *Church-Rosser $\rightarrow_{\beta\eta}$ satisfy the Church-Rosser property.*

Now let take a moment to comment on the usefulness of each reduction. We can say that β reduction is the soul of computation while η is useful to cleanup the results. In fact, Church-Rosser is also stated in an alternative form that only includes β -reduction, with a rather similar proof that we omit, but can be checked in [Theorem 1.32, [14]].

Theorem 3.1.5. *\rightarrow_{β} satisfy the Church-Rosser property.*

This theorem gives coherence to the definitions, as it states that any two deduction are basically the same but for the order of the steps. Therefore we can consider λ -calculus and operate, with α -equivalence and $\rightarrow_{\beta\eta}$ reduction to derives terms. This can be used to define *normal* forms for untyped lambda-terms. More information on normalization can be found on [29].

3.1.2 Fixed points and Programming

In this subsection we expose the basic rudiments for programming in untyped lambda calculus. In particular, we explain how to define, for example, a booleans, an integer type and a recursion operator, thus showing the computational potential of recursively enumerable languages. We start with the booleans.

Definition 3.1.14 (Boolean in untyped lambda-calculus). We define the two values T and F , true and false, as:

$$\begin{aligned} T &= \lambda xy.z \\ F &= \lambda xy.z \end{aligned}$$

We also define the operations:

$$\begin{aligned} \text{Not} &= \lambda a.aFT \\ \text{And} &= \lambda ab.abF \\ \text{Or} &= \lambda ab.aTb \end{aligned}$$

We can check that this construction left us with the basis of a boolean logic, after checking the truth values of the different operations provided. This definition of truth value is really convenient, as it allow us to easily implement control flow of programs.

Definition 3.1.15. We define the If $= \lambda x.x$.

We can see that in this case, $\text{If } TMN = M$ and $\text{If } FMN = N$. This construction is very natural and widely used in computer programs. Next, we will define Naturals number.

Definition 3.1.16 (Natural numbers in untyped lambda-calculus). Let f, x be fixed lambda terms, and write $f^n x = f(f(\dots(f(x))\dots))$. Then, for each $n \in \mathbb{N}$, we define the n th Church numeral as $\bar{n} = \lambda f x. f^n x$.

Finally, we consider the notion of recursive function. This is done with a elegant artefact, based on an idea of fixed points. Let's begin:

Theorem 3.1.6 (Fixed points). *For every term F in untyped lambda calculus, there is a fixed point.*

Proof. Let $A = \lambda xy. y(xy)$ and $\Theta = AA$. Then, for every lambda-term F we have that $N = \Theta F = FN$, thus being a fixed point. In fact:

$$N = \Theta F = AAF = (\lambda xy. y(xy))AF \rightarrow_{\beta} F(AAF) = F(\Theta F) = FN.$$

□

The proof of this theorem led to a new definition:

Definition 3.1.17. The term Θ used in the previous theorem is called *Turing fixed point combinator*.

This existence of fixed point theorem is really useful, as we can now define *recursion*. The idea is to define a function as a term with itself as a parameters and proceed to evaluate a fixed point. Let us first present an example.

Definition 3.1.18. We define the terms:

$$\begin{aligned} \text{add} &= \lambda nmfx. nf(mfx), \\ \text{mult} &= \lambda nmf. n(mf), \\ \text{iszero} &= \lambda nxy. n(\lambda z. y)x, \\ \text{predecessor} &= \lambda n. \lambda f. \lambda x. n(\lambda g. \lambda h. h(gf))(\lambda u. x)(\lambda u. u). \end{aligned}$$

Suppose that we want to define the factorial such that

$$\text{fact } n = \text{If}(\text{iszero } n)(1)(\text{mult}(n)(\text{fact}(\text{pred}(n)))),$$

in order to do that, we can simply see of all terms, what is a fixed point of:

$$\lambda f. \lambda n. \text{If}(\text{iszero } n)(1)(\text{mult}(n)(f(\text{pred}(n)))),$$

and thus $\text{fact} = \Theta \lambda f. \lambda n. \text{If}(\text{iszero } n)(1)(\text{mult}(n)(f(\text{pred}(n))))$. In general:

Definition 3.1.19. Given an stop condition g , an stop value s and a recursive step f , we define the recursive term F that computes (g, s, f) as

$$F = \Theta \lambda f. \text{If}(gn)(n)(f(\text{pred}(n)))$$

Another implementation of the fixed point operator is *Curry's paradoxical fixed point operator*:

Definition 3.1.20. We define Curry's paradoxical fixed point operator Y as:

$$Y = \lambda f. (\lambda x. f(xx))(\lambda x. f(xx)).$$

This operator is used for the Curry's paradox.

3.1.3 Rosser-Kleene and Curry's Paradoxes

In this subsection we explain the deficits in untyped λ -calculus, that was the original Church construction, that eventually leads into the definition of *typed λ -calculus*.

An aproximation of this argument can be done if we consider domains of functions to be sets. In particular untyped λ -calculus allow functions to be applied to themselves. This is going to be troublesome, considering domains as sets, as this will be a clear infringement of *ZF Axiom Theory*[20]. Namely, the infinite descending sequence

$$f \ni \{f, f(f)\} \ni f \ni \{f, f(f)\} \dots$$

in contradiction with the *regularity axiom*. An approach that seek solving this problems is presented in the next section, starring the introduction of types.

This last idea, despite being clear and loud to the intuition, is not a proof of inconsistency as there is no need for domains to be sets. Nonetheless, there was another problem that is to be deal that was noticed before. λ -calculus was proposed to be a deductive system. The *Kleene-Rosser paradox*, first exhibited in [18] proved that simply typed lambda calculus is inconsistent. This paradox was perfected in 1958 by Curry [10] with the so called *Curry's paradox*.

To solve these problems, a very natural idea is included: the use of types in our computation system. This idea is very natural nowadays, as nearly everyone learns to program priors to a deep academic career. However, we must not forget that the origin was not to use types because we liked them initially, but because they really allow us to avoid logical problems.

3.1.4 Lambda calculus as a computation system

Around 1930, people start thinking about what mean for a function to be computable. There were three major answer to this question (section 4, [3]):

- In 1930s Alonzo Church introduces the notion of λ -calculus, in which a function is computable if we can write it as a recursive-lambda term onto Church's numerals, that is, if we can deduce the result after a (hopefully finite) deduction steps.
- Later, Alan Turing, who had previously been a doctoral student of Alonzo Church, developed the concept of the Turing machine, in which a function

is computable if a tape machine with a limited set of operations is capable of reproducing it.

- Meanwhile, Gödel define the computable function as the minimum set of function such that some properties (such as the existence of a successor function) are included, and is closed under some operations.

The goal of these three mathematicians was to solve the Entscheidungsproblem[13].

The interest for this type of problems was clear for the mathematical community as the goal was to propose an algorithm that solve every theorem and can be computed. The Church-Turing thesis formally proved that these three independently generated notions were in fact equivalent[8].

This thesis is also formulated in a philosophical background, to state that every effective computable function system is equivalent to those three. While it can not be formally proven, it has near-universal acceptance to date. Any computing system that can replicate, and thus is equivalent, to either Turing Machines Calculus or Lambda Calculus is said to be *Turing Complete*.

Nonetheless, after the formalization of the solution of this problem there were a last problem that was not adverted: the finiteness of time. SAT is the problem that has as input a propositional logic formula and solve whether it is satisfiable. This problem is NP-complete, quite famously the first of these problems[7]. If we consider the analogous problem for first order algebra, we have an even more complex P-space-complete problem, being almost intractable in worst cases to this date. As a happy consequence for us, much work is left to be done in this area [6].

3.2 Typed Lambda Calculus

Typed λ -calculus is a refinement of untyped λ -calculus, presented as a for the Rosser-Kleene paradox. In this we will introduce the concept of typing. This idea is intended to restrict the ability of types to combine with each other. We start defining *simply typed λ -calculus*, on which we only consider a handful of basic types, and product and function types. In opposition we can study *dependent typing*, where types can be constructed onto each other.

3.2.1 Definition

We synthesize the definitions of typing presented in [21] or [29]. We structure this definition in three steps: types, formulas (sometimes called terms) and equations.

Definition 3.2.1. The types of simply typed λ -calculus are built via the BNF:

$$A, B ::= \iota \mid A \rightarrow B \mid A \times B \mid 1.$$

where ι denote a basic type.

As it happens in sets, where we have that we can consider the set of functions between two sets, here we can consider the type of function between two types. Surely this can get to mind a categorical construction already presented. We continue defining the formulas. Further on, we will use formulas and terms interchangeably. This

types are called *function types*.

Definition 3.2.2. The *raw typed lambda terms* of simply typed λ -calculus are built via the BNF:

$$A, B ::= x \mid AB \mid \lambda x^t. A \mid \langle A, B \rangle \mid \pi_1 A \mid \pi_2 A \mid *.$$

where x denote any variables, and t denote any type.

In this definition we intend to define π_i in a way that $\pi_i \langle A_1, A_2 \rangle = A_i$, and such that $*$ is the only term of type 1.

The main difference with untyped calculus, is that every bound variable has a type. That is, for the expression $(\lambda x^t. M)N$ to be coherent we require N to be of type t . This led us to require some sort of condition to N for being of type t .

Nonetheless raw terms have some other meaningless terms, such as projections of a non-pair $\pi_1(\lambda x^t. x)$. We solve all this problems at once with the *Typing rules*. This rules will restricts the semantics of terms. We start by defining *typing context*.

Definition 3.2.3. When a term M is of type t , denoted as $M : t$. A typing context is a set of assumption $\Gamma = (x_1 : A_1)$, on which we assume each variable x_i to be of type A_i .

From this definition, we can state the typing rules, from which we will be able to provide typing. We use the notation $\Gamma \vdash M : A$ meaning that the typing context Γ derives in term M being of type A .

Definition 3.2.4 (Typing Rules). We define the following typing rules, for each typing context Γ .

- Every variable is of the type marked by the context, namely:

$$(var) \quad \frac{}{\Gamma \vdash x_i : A_i}, \quad i = 1, \dots, n.$$

In addition, $*$ is of type 1.

$$(*) \quad \frac{}{\Gamma \vdash * : 1}.$$

- From a term of type $A \rightarrow B$ we can derive a term of type B , from a term of type A :

$$(app) \quad \frac{\Gamma \vdash M : A \rightarrow B \quad \Gamma \vdash N : A}{\Gamma \vdash MN : B}.$$

Conversely, we can deduce th

$$(abs) \quad \frac{\Gamma, x : A \vdash M : B}{\Gamma \vdash \lambda x^A. m : A \rightarrow B}.$$

- The projections takes types pairing to each typing:

$$(\pi_i) \quad \frac{\Gamma \vdash M : A_1 \times A_2}{\Gamma \vdash \pi_i M : A_i}, \quad i = 1, 2,$$

and conversely:

$$(pair) \quad \frac{\Gamma \vdash M : A \quad \Gamma \vdash N : B}{\Gamma \vdash \langle M, N \rangle : A \times B}.$$

Note that not every term can be typed, namely the two previous examples of bad-behaviour: $\pi_1(\lambda x^t.x)$ and $(\lambda x^t.M)N$ where N is not of type t . Thus, in simply typed lambda calculus, we only work with typed terms.

Definition 3.2.5. A *simply typed lambda term* is a raw typed lambda term that, together with a typing context of every variable, is subject to be typed.

By assigning type we mean assigning types to the free and bound variables. Further on, when talking about terms we will refer to simply type lambda terms. On these terms, we can define substitution just like we defined it on untyped lambda calculus.

3.2.2 Unification of typing

We can consider two standards in typing: *Church Style* and *Curry Style*.

- Church style, first shown in [4], is an explicit system, as we do only consider expression with well defined types, in the same way that a function is consider with regard to it domain and codomain. In summary, the typing of a function is the first part of the definition of it, so you can define $f : (0, 1) \rightarrow (0, 1)$ and just then define $f(x) = 1/x$. This domain is not it only possible domain, but it what we choose it to be.
- Curry style on the other hand, gain some of the notions of untyped λ -calculus and consider expression as function. To continue the real function analogy, it consider that the function $f(x) = x^2$ just exists, and one can check that it is well defined on \mathbb{R} .

More information about the typing style can be found on Chapter 10 and 11 of [14].

Despite this apparent differences, both typing styles can be *unified*. An unifier is a pair of substitution that makes two type styles equal as typed templates. Such an unifier is based on an algorithm based on type inference. This is instrumental to languages as relevant python, that works with implicit typed variables. How this algorithms for unification is shown in great detail in chapter 9 of [29]. Due to this unification, we can consider only explicitly typed terms without any remorse.

3.2.3 Church-Rosser on simply typed lambda calculus

To talk Church-Rosser, we have to talk reduction. Reductions are basically the same but for the additional structure added that we need to respect:

Definition 3.2.6 (Section 2.5 [29]). We define the *single-step β -reduction* as the smallest relationship \rightarrow_β such that:

$$(\beta): (\lambda x^t.M)N \rightarrow_\beta M[N/x].$$

$$(\beta_{\times,i}): \pi_i \langle M_1, M_2 \rangle \rightarrow_\beta M_i.$$

$$(\text{cong}_1): \text{If } M \rightarrow_\beta M' \text{ then } MN \rightarrow_\beta M'N.$$

(cong₂): If $N \rightarrow_\beta N'$ then $MN \rightarrow_\beta MN'$.

(ζ): If $M \rightarrow_\beta M'$ then $(\lambda x.M) \rightarrow_\beta \lambda x.M'$.

We define the *multiple-step β -reduction* \twoheadrightarrow_β as the reflexive, transitive closure of \rightarrow_β .

Definition 3.2.7. We define the single-step η -reduction \rightarrow_η as the smallest relationship such that:

(η): $(\lambda x.Mx) \rightarrow_\eta M$, para todo $x \notin FV(M)$.

(η_1): $\langle \pi_1 M, \pi_2 M \rangle \rightarrow_\eta M$.

(η_\times): If $M : 1$ then $M \rightarrow_\eta *$.

(cong₁): If $M \rightarrow_\eta M'$ then $MN \rightarrow_\eta M'N$.

(cong₂): If $N \rightarrow_\eta N'$ then $MN \rightarrow_\eta MN'$.

(ζ): If $M \rightarrow_\eta M'$ then $(\lambda x.M) \rightarrow_\eta \lambda x.M'$.

Similarly, we define the multiple-step η -reduction \twoheadrightarrow_η as the transitive reflexive closure of \rightarrow_η , and the η -equivalence as the symmetric closure of \twoheadrightarrow_η .

We can now talk about Church-Rosser. Lets check that it does not hold. For example, if $x : A \times 1$ then we can consider $M = \langle \pi_1 x, \pi_2 x \rangle$. Because of the rule η_1 , we have that $M \rightarrow_\eta \langle \pi_1 x, * \rangle$, but taking η_\times into account we can check that $M \rightarrow_\eta x$.

Despite this, β -reduction does maintain the Church-Rosser property, so from a computational point of view there is no problem at all.

3.2.4 Expanded Typing

We can add to the definition of typing by considering the sum Type. The idea is to have two types A and B and be able to consider a term $\lambda x^{A+B}.x + 1$. That is, we can consider two types to be acceptable by a function. This notion, commonplace in engineering, has to be formalized to be acceptable:

Definition 3.2.8. The types of expanded simply typed λ -calculus are built via the BNF:

$$A, B ::= \iota \mid A \rightarrow B \mid A \times B \mid A + B \mid 1 \mid 0.$$

where ι denote a basic type.

We proceed to define the raw typed lambda terms. We have the same consideration as previously, so that only those being subject to typing will be considered terms. Unification of typing considerations also holds.

Definition 3.2.9. The *expanded raw typed lambda terms* of simply typed λ -calculus are built via the BNF:

$$A, B, C ::= x \mid AB \mid \lambda x^t. A \mid \langle A, B \rangle \mid \pi_1 A \mid \pi_2 A \mid * \\ \mid \text{in}_1 A \mid \text{in}_2 A \mid \text{case } A; x^{t_1}. B \text{ or } x^{t_2}. C \mid \Box^t.$$

where x denote any variables, and t denote any type.

Probably the only exotic of this term is $\text{case } A; x^{t_1}. B \text{ or } x^{t_2}. C$. This abstracts the idea that a union term behaves differently in each type that is included. In the typing laws we will see that it is necessary that the type returned by the application of a variable in a function of type union must always converge to the same type (*case rule*).

For this typing, three new rules are included for type derivation, in addition to the previously defined in 3.2.4:

Definition 3.2.10 (Typing Rules). We define the following typing rules, for each typing context Γ .

- Every type is part of a union type including it:

$$(\text{in}_i) \quad \frac{\Gamma \vdash M : A_i}{\Gamma \vdash \text{in}_i M : A_1 + A_2}, \quad i = 1, 2.$$

conversely, A term on a union must always have the same type after application.:

$$(\text{case}) \quad \frac{\Gamma \vdash M : A + B \quad \Gamma, x : A \vdash N : C \quad \Gamma, x : B \vdash P : C}{\Gamma \vdash \text{case } A; x^A. M \text{ or } x^B. P : C}.$$

- The \Box extract a term of any type from the void type.

$$(\Box) \quad \frac{\Gamma \vdash M : 0}{\Gamma \vdash \Box^A M : A}.$$

3.3 Curry-Howard bijection

3.3.1 Natural deduction

In this section we succinctly introduce the notation of propositional intuitionistic logic, in order to work with them further in the chapter. Therefore, we spare our readers of yet another comprehensive introduction of the widely known propositional logic. Should it be required, more information of propositional logic can be found in, for example, [23] and [32]. Natural deduction originally appears in the works of [11].

Thorough this section we replicate notations and process done when defining typed lambda calculus. This is done purposely, as our aim is to proof an equivalence between both system. We start by considering the alphabet consisting a set of countable many variables x, y, z, \dots as done previously in lambda-calculus, \top and \perp .

Definition 3.3.1. The formulas of propositional intuitionistic logic are built via the BNF:

$$A, B ::= x \mid A \rightarrow B \mid A \wedge B \mid A \vee B \mid \top \mid \perp.$$

where x denote any variable.

Note that we consider a logic without law of excluded middle. This approach, although somewhat demodé in modern mathematics, was highly popular at the beginning of the twentieth century. It sought to solve the problems of mathematical foundations, in particular the *principle of explosion*.

Having the syntax done, is time to provide meaning. We want \top to be the truth value. A formula is true if $A \rightarrow \top$. Conversely, a formula is *not-true* or *false* (sometimes denoted as $\neg A$) if $A \rightarrow \perp$. In addition, we want all the formulas from which we can derive certain to be true. For this we will define, analogously to the typing-context from the previous chapter, what a *truth-assumption* is and what the rules of deduction are.

Definition 3.3.2. A truth-assumption is a set of variables $\Gamma = \{x_1, \dots, x_n\}$ that we assume to be true. An *judgement* $\Gamma \vdash B$ states that from truth assumption Γ , the formula B can be deduced to be true.

Sometimes we can write a truth assumption Γ, A , that will denote that additionally A is assume to be true. As most times, we will only need a formula A to be true or not without any interest on what exact variable configuration made this possible, so by abuse of notation we can consider $\Gamma = \{x_1, A_1\}$ to have both variables and formulas.

Definition 3.3.3 (Deduction Rules). We define the following deduction rules, for each truth assumption Gamma $\Gamma = \{x_1, \dots, x_n\}$.

- Every variable assumed to be true is true:

$$(ax) \quad \frac{}{\Gamma \vdash x_i}, \quad \forall i \in 1, \dots, n.$$

In addition, \top is always true:

$$(\top) \quad \frac{}{\Gamma \vdash \top}.$$

- From a true formula $A \rightarrow B$ and a true formula A , B can be derived:

$$(\rightarrow_1) \quad \frac{\Gamma \vdash A \rightarrow B \quad \Gamma \vdash A}{\Gamma \vdash B}.$$

Conversely, if assuming A deduces B , then $A \rightarrow B$ is true.

$$(\rightarrow_2) \quad \frac{\Gamma, A \vdash B}{\Gamma \vdash (A \rightarrow B)}.$$

- The conjunction being true imply each element to be true:

$$(\wedge_1) \quad \frac{\Gamma \vdash A_1 \wedge A_2}{\Gamma \vdash A_1, \quad \Gamma \vdash A_2},$$

and conversely:

$$(\wedge_2) \quad \frac{\Gamma \vdash A \quad \Gamma \vdash B}{\Gamma \vdash A \wedge B}.$$

- Every type is part of a union type including it:

$$(\vee_1^i) \quad \frac{\Gamma_i}{\Gamma \vdash_{\in_i} A_1 + A_2}, \quad i = 1, 2.$$

conversely, A term on a union must always have the same type after application.:

$$(\vee_2) \quad \frac{\Gamma \vdash A \vee B \quad \Gamma, A \vdash C \quad \Gamma, B \vdash C}{\Gamma \vdash C}.$$

- the *ex falsum quodlibet* (i.e. everything is derivable from falsity) holds:

$$(\perp) \quad \frac{\Gamma \vdash \perp}{\Gamma \vdash A}.$$

So, what properties make this logic interesting? By not having the law of the excluded third, we have a system in which all proofs must be constructive. Therefore, we can view proofs as programs. We will formalize this idea of viewing proofs as programs in the next section, by relating our computational system and our intuitionistic logic.

To work with this logic, we usually work in the usual *truth derivation*. That is, having a formula F , we use the previously introduced rules in other to see whether can they be derivated from the truth assumption. More often than not, we consider the empty assumption, therefore we are working with *tautologies*

Example 3.3.1. We can consider the formula $F = ((x \rightarrow y) \wedge (y \rightarrow z)) \rightarrow ((x \rightarrow z))$ and Γ the empty assumption. Then we can deduce:

$$\begin{aligned} \Gamma &= \{\} \vdash ((x \rightarrow y) \wedge (y \rightarrow z)) \rightarrow (x \rightarrow z), \\ \Gamma &= \{(x \rightarrow y) \wedge (y \rightarrow z)\} \vdash (x \rightarrow z), \\ \Gamma &= \{(x \rightarrow y), (y \rightarrow z)\} \vdash (x \rightarrow z), \\ \Gamma &= \{(y \rightarrow z)\} \vdash (y \rightarrow z), \\ \Gamma &= \{\} \vdash \top. \end{aligned}$$

therefore the formula F is true.

As a final note, the definitions of intuitionistic logic and lambda calculus introduced in this work, are made to be matching but are not unique. For example, other source consider that the types of simply typed λ -calculus (instead of the extended typing) and consider only (as is done in [29, Section 6.5]):

$$A, B ::= x \mid A \rightarrow B \mid A \wedge B \mid \top.$$

This is called *positive intuitionistic calculus*. We decided not to follow this line, which is equally valid, for consistency with [28] However, it is useful to have this consideration resolved from the beginning, especially for engineering applications.

3.3.2 Bijection

The first approach of lambda calculus to be seen as a deduction system was observed by Curry in 1934[9], early in the development of this area.

Having already asked ourselves when does a term have a type, it is natural to arise the new question: When does a type have a term? This is in fact the fundamental idea of the Curry-Howard isomorphism. For example, considering whether it exists a term for the type $(A \times B) \rightarrow B$, is analogue to consider the formula $(A \wedge B) \rightarrow B$ to be a tautology. Moreover, the term $\lambda x^{A \times B}. \pi_2 x$ can be seen as a proof of the tautology!

we have arrived at the dream of a constructivist mathematician: computational algorithms are demonstrations, and demonstrations are nothing if not algorithms. Lets formalize this intuition.

We can create a pairing between type and formulas by pairing variables with variables and:

Types	Formulas
Type 1	\top
Type 0	\perp
Function type \rightarrow	Implication \rightarrow
Product type \times	Conjunction \wedge
Sum type $+$	Disjunction \vee

Pairing of formulas and terms.

And we can see that this pairing holds because we can see that Typing rules

- We pair the concept of a formula being true with the concept of a type having a term. We formalize this by pairing truth assumption $\Gamma = \{A\}$ is with the typing context $\Gamma \vdash M : A$.
- We can relate (var) with (ax) and $(*)$ with (\top) .
- We can relate (app) with (\rightarrow_1) and (abs) with (\rightarrow_2) .
- We can relate (π_i) with (\wedge_1) and (\wedge_2) with $(pair)$.
- We can relate (in_i) with (\vee_1^i) and (\vee_2) with $(case)$.
- We can relate 0 with \perp .

With this construction we have develop a pairing in syntax, now we can make a pairing in semantics. The million dollar question is: Who do we relate the concept of term with? We relate it with the concept of truth derivation. That is, given a term M of type C with associated formula F . By replacing each typing rule needed to deduce $M : C$ with an associated derivation rule, we can get a truth derivation, and conversely with a truth derivation of $F \rightarrow \top$ from $\Gamma = \{\}$.

We can mentioned prior, we can vary lightly the definitions, but an analogue pairing still holds. For example, we can consider an intuitionistic logic where there is no \vee nor \perp in a pairing with (unextended) simply typed. Further on the text we will examine this variation of pairings.

Chapter 4

Curry-Howard-Lambeck bijection

In these chapter we raise bridges between Category Theory, Lambda calculus, and Propositional logic. The main sources for this chapter were [21] and [29, Chapter 6].

4.1 Deduction systems

4.1.1 First Definitions

Deduction systems

Having introduced the notion lambda calculus, category theory and propositional intuitionistic calculus, is time to have a step back, in other to get the full picture.

Definition 4.1.1. A *Deductive system* D is a graph with identity and composition of arrows.

We can reformulated the previous logic with this optic. Prior to that we will make an illustrative example on how is this made. All the properties aforementioned (and paired) show that the requirements of typing/intuitionistics calculus can be expressed in just requirements for the arrows. For example,

Example 4.1.1. 1. Deduction rule \rightarrow_1 : There is an arrow

$$\varepsilon_{A,B} : [B \wedge (B \rightarrow A)] \rightarrow A.$$

2. From deduction rule \rightarrow_2 it can be deduced:

$$\begin{aligned} \Gamma, \{ \} \vdash F &= (C \wedge B) \rightarrow A; \\ \Gamma, \{ (C \wedge B) \} \vdash A; \\ \Gamma, \{ C, B \} \vdash A; \\ \Gamma, \{ C \} \vdash B \rightarrow A; \\ \Gamma, \{ \} \vdash F' &= C \rightarrow (B \rightarrow A). \end{aligned}$$

That is provided an arrow $h : C \wedge B \rightarrow A$ there is an induced arrow

$$h^* : C \rightarrow [A \rightarrow B].$$

We can unpack a bit from these notions. To begin with, we can check that the second example include an idea, much needed, in the relationship between assumption and deduction systems. We can view each assumption of truth as a new deduction system. This also seems logical, since an assumption $\Gamma = \{A_i : i = 1, \dots, n\}$ with A_i

formulas can be seen as an existence of an arrow $g_i : \top \rightarrow A_i$.

We see that in our derivations we sometimes need to change the truth-assumption Γ . This is not mandatory, but it is useful to avoid including a large number of rules. However we do that in a way such that we start from a given Γ and return to it at the end of the derivation. Thus knowing that if a Γ derives the formula F , then it also derives the formula F' and therefore there is an arrow in our deductive system. Similar reflections can be made with the rest of the rules discussed in the previous sections, and of course with the simply typed lambda calculus.

Logical Systems as Deduction systems

In the fashion of previous definitions we can reformulate the logical systems as deduction systems.

Definition 4.1.2. A conjunction calculus is a deductive system D where there is a specified object \top and an operation $\wedge : Ob(D) \times Ob(D) \rightarrow Ob(D)$ such that:

1. For each $A \in Ob(D)$ exists $O_A : A \rightarrow \top$.
2. For each $A_1, A_2 \in Ob(D)$ exists arrows $\pi_i^{(A_1, A_2)} : A_1 \wedge A_2 \rightarrow A_i$ for $i = 1, 2$.
3. Let $f : C \rightarrow A$ and $g : C \rightarrow B$. Then $\langle f, g \rangle C \rightarrow A \wedge B$.

Note that $\pi_i^{(A_1, A_2)}$ depend on both A_1, A_2 . in the absence of ambiguity we will denote this arrow by π_i .

Definition 4.1.3. A positive intuitionistic calculus is a conjunction calculus D where there is binary an operator $\rightarrow : Ob(D) \times Ob(D) \rightarrow Ob(D)$ such that:

1. For each $A, B \in Ob(D)$, there is an arrow $\varepsilon^{A,B} : [(B \rightarrow A) \wedge B] \rightarrow A$.
2. For each $g : C \wedge B \rightarrow A$ then there is an arrow $g^* : C \rightarrow [B \rightarrow A]$.

Remark 4.1.1. Note that we use $[]$ to avoid ambiguity between \rightarrow as operator or as simply an arrow.

Similarly to π_i , we will usually denote jsut ε .

Definition 4.1.4. A *intuitionistic propositional calculus* is a positive intuitionistic calculus where there is a specified object \perp and an operation $\vee : Ob(D) \times Ob(D) \rightarrow Ob(D)$ such that:

1. For each $A \in Ob(D)$ there is an arrow $\Box_A : \rightarrow A$.
2. For each $A_1, A_2 \in Ob(D)$ there are arrows $\sqcup_i : A_i \rightarrow A_1 \vee A_2$.
3. For each $A, B, C \in Ob(D)$ there is an arrow

$$h : [(B \rightarrow A) \wedge (C \rightarrow A)] \rightarrow [(C \vee B) \rightarrow A].$$

Categorical systems as Deduction systems

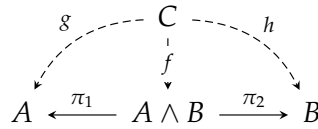
We have already note how a category is a particular case of a deduction system. We can consider how are the logical systems, but we only select those who are also categories.

Proposition 4.1.1. A cartesian category C is a deduction system that is both conjunction system and a category where:

1. $f : A \rightarrow T \implies f = O_A$.
2. Given $\langle f_1, f_2 \rangle : C \rightarrow A \wedge B$ then $\pi_i \circ \langle f_1, f_2 \rangle = f_i$.
3. Given $h : C \rightarrow A \wedge B$ we have that $\langle \pi_1 h, \pi_2 h \rangle = h$.

Proof. Lets begin by proving that a cartesian category satisfy this conditions. It is clearly a category. Using the specified terminal point $T = \top$. Considering the product $A \times B = A \wedge B$ for every $A, B \in C$ along with the projections, the others properties are satisfied.

Conversely, considering again $T = \top$ we can check that it is a terminal object. Also, for every $h : C \rightarrow A \wedge B$ we can see that every h derive the existence of unique f_1, f_2 such that:



And thus we have finite product. □

Thus, we can start seeing the kind of bijection already shown in the Curry Howard Isomorphism. Hitherto we can adopt the notation $A \times B$ for the conjunction, in the context of cartesian categories.

Proposition 4.1.2. A closed cartesian category C is a deduction system that is a positive intuitionistic calculus that is also a category such that:

1. For all $h : C \times B \rightarrow A$, we have that $\varepsilon \langle h^* \pi_1, \pi_2 \rangle = h$.
2. For all $k : C \rightarrow [B \rightarrow A]$, we have that $(\varepsilon \langle k \pi_1, \pi_2 \rangle) = k$.

Proof. Lets begin checking that C is a positive intuitionistic calculus and holds 1. and 2. As it is a cartesian category, by it does satisfy the requirements for being a conjunction calculus. Pairing the exponential object cA^B with the function object $B \rightarrow A$. As in definition 2.2.6, we have two functors F_3 and G_3 , that are both adjoint, i.e.:

$$\text{hom}_C(C \times B, A) \equiv \text{hom}(C, A^B)$$

Then, by proposition 2.2.1, we can deduce the existence of a natural transformation $\varepsilon^{A,B} : FG \rightarrow I_C$ such that every $(x) : Fx$

To do the converse, is enough to made the same pairings and apply 2.2.2 to check that such adjoints are define via ε . □

These propositions allow us to easily define graph completions to generate a to generate from these CCCs and positive conjunction calculus.

4.1.2 Natural Numbers

4.1.3 A language from a Closed Cartesian Category

The internal Language

Explain Example 10.6 and proposition 10.7

Equivalence

After defining L we want to show that it is an equivalence of categories. We shall obtain a functor C in the opposite direction.

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